



**Terrestrial
Oceans
and Lunar
Maria**

G.F.Makarenko

Mir Publishers Moscow

Both the Earth and the Moon have been repeatedly involved in episodes of volcanic activity induced by the heating of the interior of the two planets. Before the onset of each epoch of outpourings of lava that filled volcanic seas, arcuate and ring-shaped mountain chains encircled these seas in different regions of the planets. The Moon is "simplified model" of the Earth. Reviewing the structures of the Earth and the Moon simultaneously, we shall better understand the origins and compositions of the mountain ranges of the Pacific coast and see why the Atlantic-type oceans are not surrounded by mountains, and what is common in the structure of the volcanic floor of terrestrial oceans and lunar maria.

The book is intended for a wide circle of geologists, geographers and astronomers and will also be of interest to those who are specializing in the geology of the Earth and the Moon.

Terrestrial Oceans and Lunar Maria

Г. Ф. Макаренко

ВУЛКАНИЧЕСКИЕ МОРЯ ЗЕМЛИ И ЛУНЫ

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Introduction

Man has long been directing his attention and thoughts to the interior of the Universe in order to determine the role of our planet as cosmic body among the other celestial bodies, he gradually acquired the knowledge of the laws of celestial mechanics. The evolution of astronomical objects is one of the oldest mysteries that have been plaguing inquisitive minds for centuries.

Man's extravehicular activity marked the beginning of a new era of cognition of the world around us. An opportunity of comparing the geological processes has appeared; these processes transform the face of our planet with those acting on other planetary bodies.

The Moon is the only satellite in the Solar system that differ fairly little from its parent planet. Its diameter is approximately one-fourth that of the Earth, and its mass is $1/80$. Because the density of the Moon is low, its volume is $1/50$ that of the Earth, and the gravity is $1/6$ that on Earth.

The Moon is roughly 400 000 km away from the Earth. Since its mass is small, the Moon is devoid not only of an atmosphere but also of water, liquid or solid. As a consequence, the Moon is the best object for studying the surface of planets outside the Earth. From the Earth quality photos discriminate relief features as small as 1.5 km on the Moon. Modern ground-based telescopes have a 300-m resolution. Finally, photographs, taken by artificial satellites orbiting the Moon, pinpoint even 1-m details. The relief forms on the Moon surface have been traced in much more detail than those in relatively inaccessible regions of the Earth's continents. As for the ocean floors on Earth, their surface is nearly a blank spot as compared with that of the Moon. The Moon is now quite near—samples of its

rocks are at scientists' hands, and the results of direct laboratory studies of lunar materials have been correlated with the materials of images of the Moon in different wavelengths. The results of spectral probing have been compared with laboratory data.

Rather detailed maps of the Moon were first compiled by the Polish astronomer Johannes Hevelius in 1647. But as early as 1611 several maps of the Moon had been prepared by G. Galilei. Almost all the names, which still exist on the modern maps of the Moon, were coined by J. Riccioli and marked on the map attached to his book published in 1651. Hevelius' and Riccioli's maps show in detail the major dark lunar depressions that are visible even to the unaided eye. On the left is the Ocean of Storms (Oceanus Procellarum), in the upper centre of the lunar disk, the circular Sea of Showers (Mare Imbrium), on the right, a diagonal chain of merging oval-shaped minor seas, Mare Serenitatis, Tranquillitatis, and Foecunditatis. Numerous craters were named after scientists (Aristotles, Archimedes, Copernicus, Galilei) or heroes of ancient myths (Hercules, Cepheus). Major mountain ranges were named by analogy with the terrestrial ones (Apennines, Alps). These maps, and also new ones, showed only the side facing the Earth.

In October 1959, the Soviet automatic interplanetary station *Luna 3* was the first to photograph the far side of the Moon by going round the satellite, and sent its TV image back to Earth. Pictures produced by 40-minute photography made it possible to compile a map of the invisible lunar hemisphere and prepare a lunar globe.

Five years later, in July 1964, the American spacecraft *Ranger 7* refined the lunar topography. In July 1965, the Soviet *Zond 3* transmitted an image of the unknown areas of the far side of the Moon, and thus its first complete map was constructed. It was found out that the far side has no maria, that is depressions with dark floors, though it has craters strewn like the visible side. On the other hand, there are large circular lowlands with floors lighter than those of the maria. They were named thalassoids, "marelike". Many craters and thalassoids were named after Russian scientists (Mendeleev, Tsiolkovsky, Korolev).

Panoramic photos of the lunar surface "at the eye level" were obtained in 1966, when the Soviet automatic station *Luna 9* first landed in the lifeless Ocean of Storms. Half a

year later, the American *Surveyor 1* made a soft landing on the lunar surface.

The *Luna 10* mission started off an epoch of systematic photo-television studies of the Moon from man-made satellites. In 1966-1967, spacecrafts rephotographed the whole lunar surface, flying around in different directions except for the polar regions. At the same time, other spacecrafts continued surveying the microrelief and surface structure.

In 1968 and 1969, lunar photographing was performed by the American astronauts on boards *Apollo 8* and *Apollo 10*. In July 1969, the crew of *Apollo 11*'s lunar capsule landed on the Moon in Mare Tranquillitatis. For the first time man walked over the surface of another planet.¹ The astronauts took photos and movie films directly from the surface and brought back to Earth the first samples of lunar rocks.

The main finding in the analysis of the samples was that the dark lunar maria are covered with a volcanic rock, basalt, which is quite similar to the terrestrial basaltic lavas ejected from the interior of our planet in the form of melt.

In August 1969, the Soviet *Zond 7* accomplished colour imaging of the Moon and brought the film back to Earth.

The first automatic station that delivered samples of lunar soil from Mare Foecunditatis (in September 1970) was *Luna 16*. In November 1970, the *Apollo 12* mission enlarged the collection of lunar samples and images. In November 1970, a reconnaissance television imaging of the terrain was begun by the first moon rover, the Soviet *Lunokhod 1*, with a laser reflector manufactured by French specialists. Within ten months it covered ten kilometres, made thousands of photos of lunar landscapes and several tens of chemical analyses of the lunar soil.

The *Apollo 17* mission of 1972 completed the American Apollo programme. The astronauts had landed on the lunar surface six times. In all, the missions had stayed on the Moon for about 300 hours, including 80 hours of excursions over its surface. About 400 kg of lunar rock samples were delivered to Earth. Six sets of instruments had been installed on the Moon.

In February 1972, the automatic station *Luna 20* landed in extremely rugged mountainous terrain north of Mare Tranquillitatis. In January 1973, *Lunokhod 2* started the extended studies of the lunar surface in eastern Mare Serenitatis. Its itinerary covered four times the distance made by *Lu-*

nokhod 1. In August 1976, the Soviet *Luna 24* took a sample of lunar soil from Mare Crisium. The sampling sites used by *Luna 16*, *20*, and *24* are located so that the samples provide information about the rock sequence exposed in the mare-continent-mare junction zone.

The aim of this book is to show that volcanism known on Earth and recently found on Io, a satellite of Jupiter, had some features in common on different planets. Volcanic manifestations, existing on Earth and the Moon have been now studied best of all, hence, they are used as a basis for comparative analysis of the conditions for the rise of volcanic rocks to the surface, the time of eruptions, and the positioning of volcanic mare on planetary bodies.

This book is based on information obtained by geologists from many countries. The extensive material concerning the volcanic seas on continents was summarized in the author's *Basaltic Fields of the Earth* published in 1978. The results of investigation of the volcanic ocean floors were taken from the *Initial Report of Deep-sea Drilling Project*, Wash., 1973-1981, published in more than 50 volumes.

The morphological analysis of the lunar surface was based on the *Complete Map of the Moon*, 1975, 1978, compiled at the Shternberg Astronomical Institute (USSR). Plantiful photographs of the lunar surface can also be found in Moon atlases; the most detailed of these was published in 1973 (edited by the American geologist P. Schultz). New data on the Moon, which are acquired at a fast rate, are annually published in the volumes of International Conferences *Lunar Science*, Texas, 1974-1981, and are summarized in *Stratigraphy of Part of the Lunar Near Side*, by D. Wilhelms, Washington, 1980. Information derived from international studies of the lunar geology and geochemistry is also presented in monographs prepared at the Institute of Geochemistry, USSR Academy of Sciences, the most recent of them being *The Lunar Soil from Mare Crisium*, Moscow, Nauka, 1980 (in Russian).

Earth:

A Planet in a Basaltic Shell

A View of the Earth from Space

An alien approaching our planet from space would call it a light-blue Planet of Clouds. From the Moon, he would see the Earth as a blue disk more than half of which is constantly covered with white cloud spots. It is hard to make out continental outlines on such a disk, though the darker oceans and the lighter continents would pop out as ragged patches from under the cloud cover. The ever-white polar snow caps would strike the eye. The contrasting colours of the Earth's surface would be blurred by the smoky shroud of the atmosphere.

Breaking through the cloud cover, the astronaut would see the globe with most of the surface concealed by the azure mass of the ocean water. Then he would name the Earth, now blue-green and glistening in the sunrays, an Ocean Planet.

But if the imaginary alien could see through the body of ocean water, or if he could slightly "raise" the water screen and the sediment that conceal the rigid Earth beneath, quite a different planet would reveal itself before his eyes. More than two thirds of this rigid Earth would be covered with a black stony shell—basaltic lavas littering the ocean floors throughout and cropping out on continents as isolated patches of traps (plateau basalts). Now the astronaut would name our rigid planet, enclosed in its extensive shell of solidified volcanic rocks, a Planet of Flood Basalts.

Nobody can surely see the rigid Earth under its water screen. Only geological evidence known to us, earthmen, could "prompt" the alien what he could observe by raising the Earth's gaseous and aqueous shrouds.

Realization of the fact that the Earth's surface is underlain by a basaltic shell would not surprise the alien. In-

deed, both Mars and Mercury, our nearest neighbours, and also the Moon, our satellite, likewise bear a more or less continuous blanket of dark lavas. On the Moon, these superficial lavas are similar black solidified basalts. However the outer basaltic shell embraces the Earth nowhere so fully, it occupies nearly 70 per cent of the surface. On the Moon, the basaltic blankets of its maria and oceans occupy about 17 per cent of its area, on the Mars, about half, and on the Mercury, probably about one third.

It has earlier been considered that the terrestrial ocean basins may be floored by the same relatively light (once viewed from space) materials like those on the Earth's continents. Scientists believed that vast tracts merely subsided to a lower level and were covered by the ocean water. But it was established long ago that at least ocean islands are more often formed just of volcanic rocks, dark basalts. Extensive dragging of the last decades and deep drilling on the floor of the World Ocean have proved conclusively that practically the whole bottom is covered by volcanic rocks, sheets of basaltic lavas. The islands surrounded by lava blankets either pierce through the lavas and are not flooded by them (for instance, Madagascar Island) or are more or less thick volcanic piles at some localities of the ocean. Such shields and cones made up of volcanic products rise from the ocean floor already covered by layers of consolidated magma extruded from the Earth's interior as a melt.

Being raised above the ocean lavas to heights of 2 to 6 kilometres, the continents appear as giant uplands, islands. The lava floor of the oceans entirely surrounds each of the six terrestrial continents. They are connected only by isthmuses—bridges overlooking the lava floor.

Along seashores, the outer volcanic shell of the globe is superimposed on the surface of continents (Fig. 1). It consists of traps, which are thus margins of the lava shell, films of solidified melts.

However, there are also trap provinces on Earth that do not merge with the ocean floor lava blankets.

Traps are often truncated at top, worn down on the raised continents. So the general shape of trap provinces and their area are inferred from either "residual" lava plateau or a dense pattern of magma channels from which lavas poured out onto the surface. Like the layer of submarine ocean lavas some trap blankets on continents are overlain by

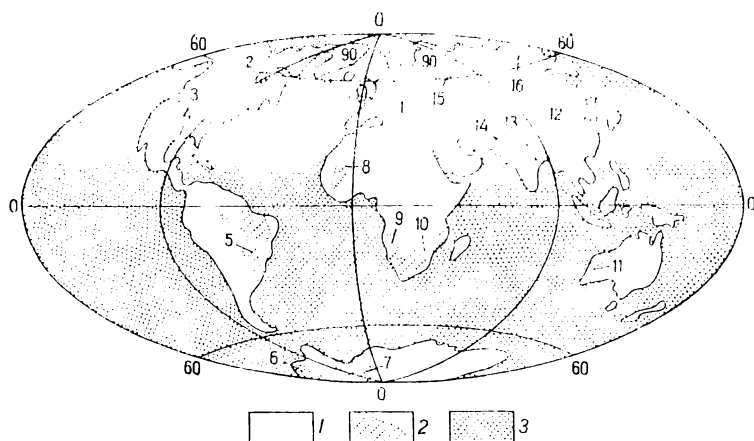


Fig. 1. Outer basaltic shell of the Earth:

1—continents projecting from the basaltic shell; 2—trap provinces on continents: 1—Great Britain, Greenland, and Spitzbergen (Brito-Arctic); 2—Canada; 3—Columbia Plateau; 4—Appalachian Mts. and the margins of the Gulf of Mexico; 5—Parana; 6—West Antarctica; 7—East Antarctica; 8—Taudent; 9—Kaoko; 10—Karoo; 11—the western part of Australia; 12—Yun-nan Province; 13—north Hindustan; 14—west and east Hindustan; 15—Siberia; 16—Verkhoyanski Khrebet; 3—basaltic shell of the ocean floor

younger sediments. One then takes into account, as for ocean volcanic sheets, areas where lavas either were drilled through at depth, beneath sedimentary strata, or were inferred from geophysical data.

The continental trap terrain makes up approximately one eighth of the modern terrestrial basaltic shell.

The lava floor of the Pacific Ocean occupies more than one third of the whole outer volcanic shell of the globe. This is roughly half of the lava floor of the World Ocean.

The Pacific Ocean is a giant circular basin that clearly makes the planet morphologically asymmetric. All the other oceans are connected by some means or other with the Pacific. Basins with the basaltic floor pass from it on the southwest to the isometric Indian Ocean, whose basaltic blanket constitutes one fifth of the basaltic shell. On the southeast, the Pacific is open toward the north-south Atlantic Ocean. The basaltic blanket of the Atlantic composes about one fourth of the basaltic shell. All these oceans make up the oceanic hemisphere of the Earth, where the outer lava film of the planet is most continuous. The continents concentrate on the other hemisphere, being separated by the

interior depression of the Arctic Ocean, which is combined with the Atlantic to the west. No drilling has been made in the Arctic, but judging from rocks on its island, it is also overlapped by a volcanic blanket. Its area is about one tenth of the total outer basaltic shell of the planet.

Different points of view were put forward concerning the origin of the basaltic blankets on the surface of the rigid Earth's crust. A common opinion of the proponents of continent motion implies that the basalts on continents differ in origin from those on the ocean floor. On continents, they issue over the continental crust, while in the ocean floor they overlie an unknown, lava-covered foundation. Also, the continental basalts differ somewhat in composition from the oceanic basalts. According to traditional geological views, however, the lavas of the ocean floor may overlie the earlier highly elevated, but now subsided continental crust. The ocean floor began to sink just when its vast expanses were flooded by deep-seated melts solidified into black basaltic rocks.

The ocean origin problem is regarded as one of the principal in modern geology. The whole World Ocean is considered to be a possible treasury of the future mineral resources of mankind. To appraise the mineral potential of the ocean, it is very important to know whether the continental areas of the crust subsided beneath volcanic rocks or the oceans formed in their own way, for instance the parts of a continent have spread aside exposing a deeper substratum flooded by volcanic melts. Comparative planetology may contribute much to the solution of this problem.

Mountains and Plains of Terrestrial Continents and Oceans

Looking at the Earth from a distance, and having removed its water shell, we could see that the whole Earth's surface is encircled by mountain ranges that pass from the elevated continents onto the low-lying ocean floors. The ranges encircle continents or dissect them as arcuate or straight-line serrated crests. Mountain ranges and their systems are intervened by plains. Some of them lie entirely on elevated continents, others slope down stepwise from continents to the margins of oceanic basins, still others are completely within lows in the ocean floor. Both the elevated and lowered plains

fill cells in the system of mountain chains on the rigid Earth's surface (Fig. 2).

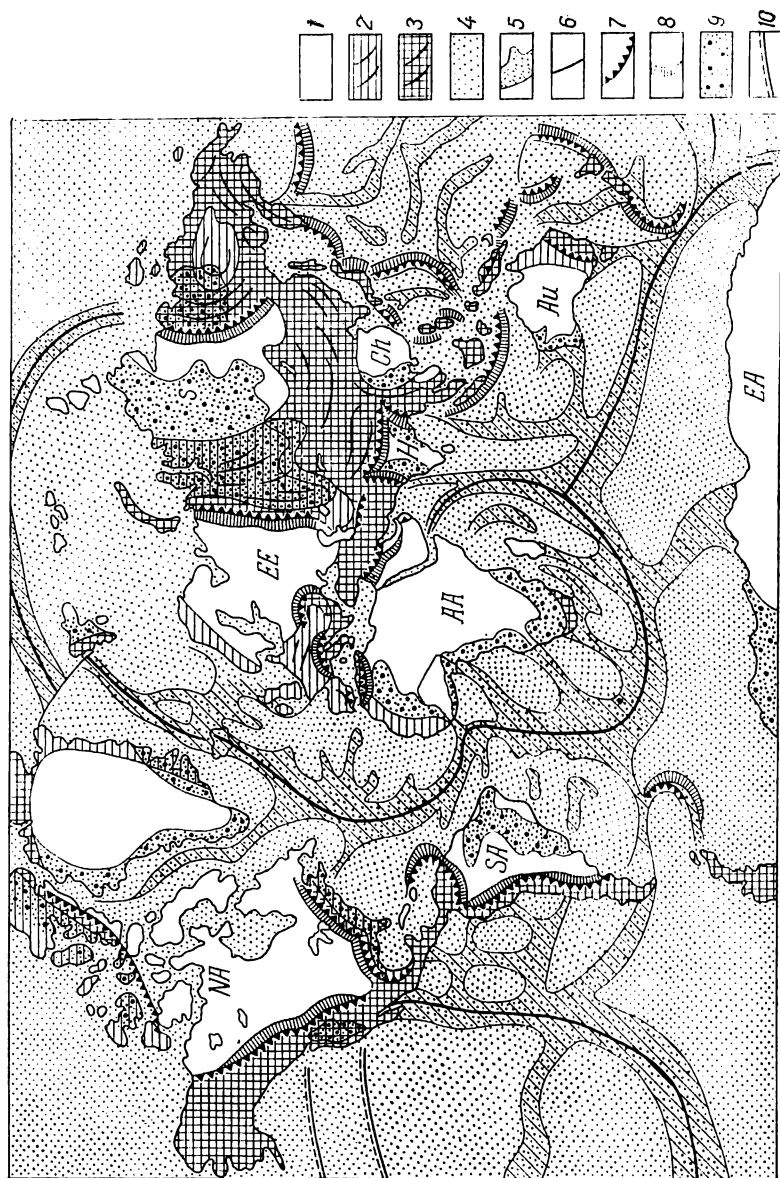
Continental plains are called platforms. They are typically covered by an extensive mantle of sedimentary strata. These strata were either accumulated by means of water sedimentation once covered by the new dry continental plains or by means of a slow redeposition of debris (fragments, sand, clay) from terrestrial streams, this debris being constantly introduced from the destructible mountains surrounding the plains.

The sedimentary strata of platforms rest on rigid crystalline basement. It is composed of folded strata injected by igneous bodies*. The basement of each platform has earlier had a rugged relief. It was itself a system of the same mountainous regions now existing only along the margins of plains. When the previous mountains had been worn down, that is denudated, there arose a levelled, plane surface underlain by folded strata that made up the earlier mountains. On sinking, the crystalline basement of the platform began to be overlain by a sedimentary cover.

The mountain chains surrounding the platform plain are built to a large extent of sedimentary strata. But if the sediments on platforms are distributed over vast tracts as thin consecutively accumulated beds, the sediments of would-be mountains are deposited in deep depressions—troughs—or in systems of closely spaced, narrow troughs usually filled up with ocean water. A totality of such troughs were called geosynclines.

When the floor of the trough subsides, or even before the main sinking event inside the depression takes place, lavas of basic magmas invariably pour out. These are just basaltic lavas that has already lost some of the volatiles of the magma. Such melts contain less silica (40-45 per cent) than acidic do. The sediments from the surrounding uplifts are transported into the trough where they alternate with lavas and overlie them. Sediments and lavas fill the troughs. At the same time, chains of volcanic islands arise inside the troughs. Volcanoes again supply melt-derived materials on slopes of island chains and in the neighbouring basins. The lava of volcanic islands which rises

* Most igneous bodies are granites of acidic magmas derived from silica-rich (over 65 per cent of silica) deep-seated melts.



from depths along ridges (cordilleras) inside the troughs is intermediate in composition between acidic and basic varieties. Such intermediate magmatic melts contain 50 to 65 per cent of silica. The volcanic cordilleras are worn down simultaneously with the development of volcanism. Gradually, the former troughs are filled completely, and the Earth here undergoes general uplift instead of previous general subsidence. Thick sequences of accumulated sedimentary and volcanic rocks are folded. Molten magma, now acidic, granitic, in composition, again rises from deep in the Earth. This time the magma is not issued onto the surface but consolidates inside a crushed strata lens accumulated in the former troughs. Because of hot magma effects and compaction as a result of crushing, the sedimentary rocks experience transformations—metamorphism—and are transformed into crystalline rocks. They are now poorly flexible and are broken in the course of further irregular uplift into lenses, slabs. During uplift, the folded strata and rigid slabs are turned inside against each other, as if turning inside out of the zone of the former trough. This turning and the displacement of geosynclinal sequences from the former troughs whose areas are then occupied by uplifts always develop unidirectionally. The folds overturn and the slabs slip and are pushed onto the plain—the stable platform region. A hundred years ago, the known Austrian geologist E. Suess called such a platform foreland, or frontal platform.

Piles of folded blocks and concave lenses of altered sedimentary and volcanic series make up mountains on continents—orogens. They are called mountains derived from geosynclines that is epigeosynclinal orogens. Now the atmospheric processes begin to destroy the mountain chains, though volcanism may continue. Mantles of metamorphic rock fragments rapidly accumulate in front of the mountains and of the slabs, packets, and overturned folds thrust

Fig 2. Mountains and plains of Earth's continents and ocean floor: 1—plains of Precambrian cratons (EE—East European; S—Siberian; H—Hindustanian; Ch—Chinese; AA—African-Arabian; Au—Australian; EA—East Antarctic; SA—South American; NA—North American, including Greenland); 2—plains of Phanerozoic platforms and principal trends of fold zones in their basement; 3—fold mountains of continents and their principal trends; 4—plains of oceanic plates; 5—mountain ranges on the ocean floor; 6—mid-oceanic ridges with median rifts; 7—margins of continental and island-arc fold ranges, shoved against the plains; 8—deep troughs in front of thrust fold mountains; 9—trap provinces—basaltic seas on continents; 10—major faults in the Pacific

over the platform. Such deposits attain a thickness of many kilometres. The substratum beneath them sinks, compensating for mountain building. These coarse-grained strata—molasse—frequently accumulate in a trough below sea level. Ultimately, the products of mountain erosion make up thick lenses of sediment. Such subsidence zones in front of mountains, filled with molasse lenses, are called fore-deeps.

The mountains still continue to rise somewhat making the axis of the foredeep roll, so to speak, toward the interior of the stable platform, the frontal frame of the fold area. While the mountains are rising, they are prominent in the relief. As soon as the uplift ceases, the mountain chains are worn down by surficial denudation geologically "instantaneously" and may become the basement of a platform beneath a sedimentary cover.

Nearly all mountain chains on continents have derived from recently sinking geosynclinal troughs. These are the Alps, Carpathians, Cordilleras, and the mountain ranges of Kamchatka and the Near East. Some mountain systems inside their separate chains still have narrow depressions lying beneath sea level. These are mountain chains of the islands of Southeast Asia and Melanesia.

Young continental mountains derived from ancient geosynclinal troughs also exist on Earth. The folded, compact series that make them up were once raised in the past as epigeosynclinal orogens. The disruption and planation of the orogens were then interrupted. Then they began to rise again, but the strata were no longer folded. The mountains rose as a whole or as massifs fragmented into blocks. Such mountains are called epiplatform. Their rise always coincides with the origin of younger epigeosynclinal mountains, which rejuvenate, as it were, their old relief. Such rejuvenated mountains are the Urals, Tien Shan, Appalachians, and some regions near and inside the Cordilleras.

Mountains rose from geosynclinal troughs many times in the Earth's history. Each epoch of mountain building and the preceding accumulation of strata that make up the mountains is called a geotectonic stage. The end of this stage is approximately determined by the moment of mountain building completion.

Mountains were generated not always simultaneously. The relationship between geotectonic stages is such that

the start of one stage (filling of a geosyncline) in some regions, takes place at the midpoint or the end of other stage (the close of orogenesis) in a nearby or distant region. It has been found that in many regions on Earth the same events occur mostly in one time and in the same succession. Hence, geotectonic stages of subsidence, sediment accumulation, and then their subsequent uplift as mountains are of a world-wide extent. And the events of these or those stages are incompatible. Some stage of epigeosynclinal mountain building occurs in some areas whereas another stage, somewhat displaced in time, in others.

On platforms, geotectonic stages are expressed as a succession of different sedimentary strata. On platforms and in the neighbouring mountain chains, the main stages of subsidence or uplift in the geosyncline may also be detected from the structure of the sedimentary cover of the platform.

From stage to stage (they also say from cycle to cycle, assuming the phenomena are to be repeated in stages) the areas that experience subsidence and subsequent mountain building reduce. The mountains built up of folded strata and adjoining the older, or already worn-down fold areas, are also degraded. They are covered by sedimentary mantles so the respective platforms are accreted, in a more or less concentric manner. This process is naturally not quite straightforward. Parts of the previous platforms may sometimes be destroyed and again involved in deep sinking of a geosynclinal type; later, mountain chains rise here again.

These processes are responsible for the modern sequence of the Earth's crust. A platform consists of two stages: the lower, crystalline basement, and the upper, a sedimentary cover; the latter is 2 to 6 kilometres thick and may not be continuous. Blocks with the exposed basement are called shields, as distinguished from sediment-covered platforms. The basement of platforms is assigned to the "granitic" layer of the crust (the name is tentative). The seismic waves penetrating the Earth's interior, propagate through it at a velocity of 6 kilometres per second. Its thickness is 15 to 25 kilometres. This layer is overlain by a denser "basaltic" layer 12 to 15 km thick, where the velocity is 6.8 to 7.5 kilometres per second. Beneath lies an interval where the velocities exceed 8 kilometres per second; this interval is assigned to the Earth's mantle. It contains lenses of asthenosphere, partially molten because of high temperatures.

Mountainous regions are underlain by crushed strata penetrated by granites. The sedimentary layer occurs here in isolated basins. The granitic layer extends to a depth of about 30 kilometres and is underlain by the basaltic layer. The higher the mountains, the greater the total thickness of crustal strata resting on the mantle. The upper boundary of the mantle is the so-called Mohorovičić discontinuity (Moho), at which there is a sharp change in seismic velocity. The inverted relationship between the height of mountains and the depth of "mountain roots", that is the thickness of the crust, is due to the effect of isostasy (the effect produced by an iceberg floating in the water).

A major role in the distribution of modern views on the ocean floor morphology is played by the American scientists B. Heezen and M. Tharp, who created expressive maps of the ocean floor relief. The latest map of the World Ocean floor morphology was prepared in 1980 under the guidance of the Soviet geologist G.B. Udintsev.

Like plains on continents, those in oceans are also covered by a sedimentary mantle. Its thickness is about 2 kilometres. The sedimentary cover overlies basaltic lavas with a velocity of 5 kilometres per second. They do not still belong to the geophysical basaltic layer. The lavas are 2 to 3 kilometres thick. Between the blanket of oceanic basaltic lavas and the basaltic layer proper, with a velocity of 6.5 kilometres per second, no crustal layer is present in many regions of the ocean that could correspond to the granitic layer of continents. The basaltic layer of oceans is thinner than the relevant layer at the base of continents. So the whole oceanic crust is thinner, varying in thickness between 7-8 to 10 kilometres. Further downward, the seismic velocity is equal to 8 kilometres per second, which is characteristic of the mantle. True, where fold mountains of island chains again pierce the blanket of oceanic lavas, the granitic layer appears again.

The geological meaning of this circumstance, namely the lack of the true or apparent crustal granitic layer, the same as the layer that underlies the sedimentary cover on continents, is still unknown. This is one of the main enigmas for the geologist. Possibly, it was never present there (the concept that the oceans are ancient). Possibly, it was present but subsided beneath lavas and ocean waters and changed its density (the concept of fixism). It may come into existence

only because of rupture of the continental shell, in gaps between the floating aside continents (the concept of mobilism).

The mountains in the ocean are also different in character. So-called mid-oceanic ridges stretch along the median line of the Atlantic Ocean, along the margin of the Pacific Ocean, and as separate branches inside the Indian Ocean. Like the ocean floor, they are also made up of basalts but not of folded and metamorphic rocks. The ridges are cut along their trend into differently elevated blocks, keys, generally with the main gorge, rift, in the middle. Deep crevices cross the ridges, with their differently elevated blocks, along faults in the ocean floor. The basaltic layer is thinning in the ocean toward the midpoint of the ridge and the top of the mantle lies here higher than beneath flat oceanic plains. But the mantle itself is less dense beneath the ridges ($V = 7.5$ km/s). This may indicate that a heated and partially molten asthenospheric lens is present there.

Major rises on the ocean floor are also swells of blocks with superstructures of volcanoes. Deep troughs, trenches, where water depth may exceed 11 kilometres, occur behind island arcs whose mountains, as on continents are made up of folded strata. The arcuate rises near trenches may be submarine; then they are built up of basaltic rocks.

All the basaltic ocean floor is flooded with lavas not older than the beginning of the Mesozoic, that is they are younger than 240 million years. But on continents, which protrude from the young lava shell, rocks are as old as 3.8 thousand million years.

The basaltic ocean floor is structurally specific. The closer to the mid-oceanic rifts, the younger the basalts that lie on the bottom. The rocks of the ocean floor also turned to be magnetic. The strips of differently magnetized rocks on the floor (alternately normal and reverse magnetization) are parallel to the rifts of the mid-oceanic ridges, as if they correspond to rock strips of different ages. These observations gave rise to a hypothesis that this alternation of the polarity of the Earth's magnetic field coincides with episodes of consecutive lava outpourings. Lavas issue on the "spreading" Earth's crust and solidify on the margins of the fissure. Then a new batch of lavas is injected inside the newly opened fissure with a new spreading of blocks of the solid Earth. Continents gradually move in different directions owing to

the accretion of the oceanic basaltic (graniteless) crust on either side of the initial crack. On the Pacific shores, the basaltic floor spreads from the ridge but does not attach to continents, submerging under them at an angle both in the west and east. In this process, the sediments on the floor are piled up along the continental margins to form folded mountains.

At once hypothesis, which is seemed to solve the two major geological problems—the formation of oceans and the origin of mountains—has been accepted widely. At the same time, once applied to particular regions, it meets with numerous controversies. It should also be taken into account that all other planets of the Earth group where undeformed circular features have been preserved evolved with the formation of basaltic “oceans” without pushing aside the crustal blocks. Here lavas flood the major crustal subsidences. That’s why it is very interesting to compare the basaltic mantles of continents and oceans on Earth with the volcanic blankets of the basaltic maria and the oceans on the Moon.

Before we discuss the origin of basalts on the ocean floor, which cannot be observed directly because of the water layer, let us consider trap provinces on continents.

Volcanic Seas of Terrestrial Continents

The volcanic seas on continents are regions of trap magmatism. As generally accepted, traps are basaltic sheets, uniform in composition that are widespread on stable plains (platforms). The basalts alternate with tuff beds made up of sprayed magma blown out by explosions. Traps also encompass conduits along which the magma rises from the interior, so these conduits are filled with solidified melt. Typical trap areas on Earth are the Deccan Plateau in Hindustan, the Parana Plateau in South America, and the Tungus region with the Putorana Plateau in East Siberia.

All rocks derived from the deep-seated melt that reached the Earth’s surface, whether they first flowed as lavas or were thrown out by volcanic explosions, are called volcanites. The outpouring of the melt is called extrusion. Solidified lavas are extrusive rocks. If the magma has not reached the Earth’s surface but consolidated in the Earth’s interior, the resultant igneous body is called intrusive, or plu-

tonic. Intrusive bodies, especially large ones, are occasionally called plutons. Intrusion, that is the injection of a trap magma into rocks, usually takes place along gently lying sedimentary strata. Such bed-by-bed intrusions are called sills. The throwing out of material by explosions is an explosive process. Rocks accumulated owing to magma explosion are tuffs or tuff breccia. When such a rock contains very large and angular clasts of alien rocks caught up by the explosion, it is named xenotuff.

The basaltic magma flows easily, unlike other types of magmatic melt coming from the Earth's interior. Magmas differ in chemical composition, mainly by silica. When it contains much silica (more than 65 per cent), the magma is considered acidic, less silica (65-55 per cent), intermediate, and still less (50-45 per cent) basic (basic tholeiitic magmas, containing 50 per cent of silica, are most widespread). Finally when the silica content is as low as 45 per cent, the magma is called ultrabasic.

Basalt is an extrusive rock, its consolidated underground equivalents, intrusive rocks, are fine crystalline (dolerite) or coarse crystalline because of slow cooling (gabbro). Both types are a lithified basic magma melt.

Each trap region occupies a huge territory, occasionally more than 1 million square kilometres. In epochs of magmatism, these huge areas received glowing flows of an incandescent melt that spread over the Earth's surface disrupting all life on its way. One flow after another, they accumulated in depressions to form lava seas.

A characteristic feature of traps is a surficial, gently lying, bedded volcanic megacover, flood basalts. Stratified basaltic covers now make up extensive tablelands markedly elevated above sea level after the accumulation of volcanites. River valleys and gulleys cut through tablelands and the solid beds of basalts stratified with loose tuff members appear on the slopes of residual hills as giant stair-steps (trappa is Swedish for stair, step).

In trap regions the identically distinct steps cut in the relief, like those formed by lavas being eroded, are created by igneous bodies emplaced in sedimentary series beneath volcanic rocks and then cut by river valleys. Stratified bodies, sills, lengthen, as it were, the trap stair-step by additional steps leading downward. They also indicate that volcanic beds lie identically, that is conformably with the

sedimentary underlayers. Thus the term traps additionally implies that the crustal block had not undergone appreciable deformation immediately before the severe event of basaltic extrusion. It mostly sank, and a pre-lava stratified sedimentary series accumulated on its surface.

The concept of traps reflects an areal, regional type of volcanic rock deposition, the present-day morphology, and the trend and dip of igneous bodies. These bodies penetrate and overlie gently lying sedimentary sequences in part of the stable plain. This plain had been subsiding slowly and receiving sediments before the epoch of volcanism and trap accumulation. It continued to sink also at the time of lava deposition and then it was elevated as a plateau and eroded by streams with the formation of a steplike relief on slopes of residual uplifts.

Lava fields derived from magma outpourings predominantly from a pattern of fissures (areal volcanism) are called fissure basalts. They are also occasionally called flood basalts. The simultaneous application of the concepts of plateau basalts and flood basalts to the lava sheet reflects the features of the terrestrial trap blanket. They also determine the modern topographic position of volcanic series (plateau basalts) and the areal type of outpourings (flood basalts).

Trap terrain of a certain age is usually called a trap province with the proper name, meaning its geographic location. A synonym of the geographic concept of a trap province is a trap field.

Any trap field is underlain by rocks derived not only from a basic magma. Each province also contains units built up of an alkaline-basic (trachybasaltic) magma and an alkaline-ultrabasic magma, particularly diamond-bearing explosion pipes—kimberlites. Rocks of the deepest magma, ultrabasic rocks proper, are always present in trap provinces. All these additional igneous rock types occur on Earth also independently of traps, that is lavas with predominating basic basalts. But in usual combinations with traps, particular sheets and intrusions derived from other magmas are always in intricate intergrowths with bodies of basaltic composition. Trachybasalts (alkaline basalts) alternate with much thicker beds of common basaltic lavas. Picrites (ultrabasic lavas) occasionally make up separate sheets. Intrusions of different types form complicated multiphase

bodies, with the magma coming from chambers at different depths.

Thus any trap province contains volcanic and intrusive rocks of a quite definite community of igneous types. In a wide sense, traps are all rocks of basic and ultrabasic compositions among which traditional basalts (tholeiites) are most widespread.

The extrusive and explosive volcanic rock piles of trap provinces can be called the short terrestrial traps. Synonyms of this term are trap megasheets and trap blankets.

In lava provinces the surface is usually occupied by a lava blanket 500-1500 metres thick. In some zones, usually along one of the margins of the trap field, the lava blanket is especially thick (up to 3 kilometres near the Enisey River of Siberia, up to 3.5 kilometres in the west of Hindustan, up to 8 kilometres and more in the east of South Africa). The lava pile is gradually thinning down toward the opposite edge of the province, and it is seen in the section that all lavas are, so to speak, a half lens.

As a rule, tuffs and tuffaceous-sedimentary rocks first few hundred metres thick lie at the base of the lava pile. They are developed extensively along the margins of trap blankets, where lavas are the thinnest. In zones with thick lava accumulations, tuffs reduce in amount, or absent at all, and terrestrial traps begin just with lavas.

Sedimentary units that underlie the trap blanket are always injected by intrusive traps that solidify at a shallow depth. The volumes and thicknesses of their bodies may be quite different. Known are giant plutons, such as the Bushveld in South Africa (more than 5 kilometres) thick and Dufek in the Antarctica (8 kilometres), however, the thickness of stratified intrusions is on the average 15 to 30 metres, more seldom up to 100 metres. Dikes are first few metres thick; some of them, which generally stretch for tens of kilometres, are as thick as 20-30 and even more than 100 metres.

We consider the structure of a typical trap province with reference to the traps of the Tungus syncline* and Taymyr. This province is located on the right bank of the Enisey River and extends from the Taymyr Peninsula to the Angara

* Syncline is a flat and very vast depression, where rocks are nearly flat lying or are very gently inclined toward its centre.

River. At its centre it coincides with the Putorana Tableland; in the east it stretches to the Anabar uplift.

The Tungus province of traps has been studied better than any other trap province of the globe. The traps of Siberia were investigated by the outstanding Soviet geologists S.V. Obruchev, F.Yu. Levinson-Lessing, V.S. Sobolev, N.S. Zaitsev, P.E. Offman, Yu.M. Sheynmann, M.L. Lur'e, G.A. Kovaleva, V.L. Masaytis, the author of this book, and also a large team of geologists from many organizations.

The subdivision of the volcanic unit into consecutively accumulated horizons, that is its stratigraphy, plays an important role in analyzing trap occurrence. The making up of trap stratigraphy is identification of contemporaneous units called formations and having different thicknesses and the establishment of a succession of their sedimentation. Geologists study fossil remains of animals and plants preserved inside the beds or imprinted on their surface. The main role in the development of stratigraphy of Siberian traps is played by V.N. Khakhlov, G.N. Sadovnikov, S.V. Meyen, and T.N. Mogucheva.

The traps of Siberia began to accumulate at the very end of the Paleozoic, namely at the close of the Permian. The main volcanic episode took place early in the Triassic, which belongs to the Mesozoic era (below the age of traps of the Tungus and other provinces of Earth will be discussed in detail).

We characterize in short the structure of the terrestrial Tungus traps bearing in mind their generally accepted subdivision into formations of different ages, to clarify the former paleogeographic conditions of accumulation of volcanites.

In the past, the traps of Taymyr were a northward continuation of the Tungus magmatic field, but then some crustal blocks rose, others tilted and sank, and the trap blanket of Taymyr turned out to be cut into strips of slabs. The Tungus syncline and the fragmented trap blanket of Taymyr was later intervened by an east-west-elongated depression, the Enisey-Khatang trough, in which the top of the traps is deeply subsided and overlain by a cover of post-trap sedimentary sequences (Fig. 3).

The lower part of the tuffs—the Tutonchan Formation—lies conformably on the coal-bearing series and consists of

ash-size particles in stratified horizons. The thickness of the formation varies between 90 metres at the Angara River to 250 metres at the centre of the syncline. Above lies the Korvunchan Formation of coarse tuffs. Its base and lower horizons contain beds of block varieties and include large basaltic bombs. Bedded varieties occur in some lenses. This part of the formation varies in thickness between 150 metres in the south to 350 metres at the centre of the syncline. Upwards in the section, the Korvunchan Formation contains stratified tuffs intercalated with tuffs of redeposited or volcanic-sedimentary varieties. The thickness of the upper part of the formation varies from south to north between 70 and 150 metres.

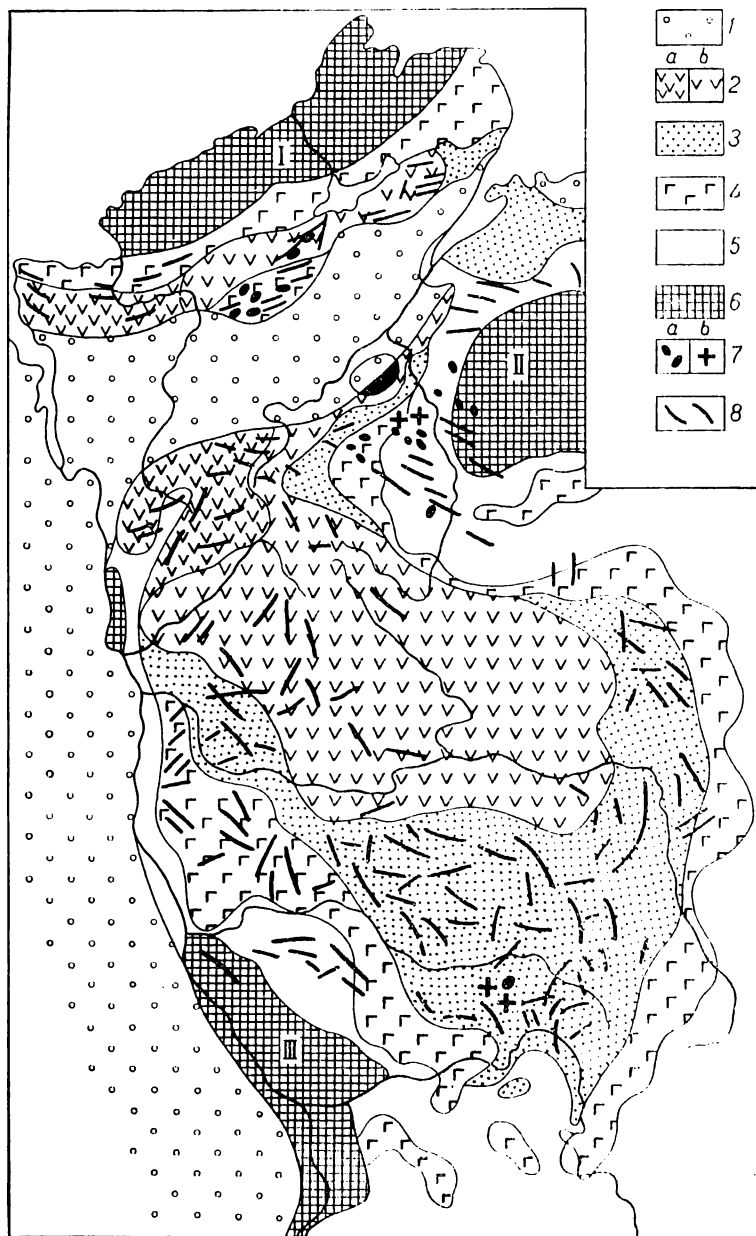
In the northwestern Tungus syncline, the coal-bearing sediments are overlain by lavas. The base of the lower basaltic sheets occasionally show indications of excavation and truncation, so to say, of the underlying strata (erosion pockets). However, neither regional structural unconformity, nor stratigraphic break is present. The lower part of the lava sequence contains specific trachybasaltic lavas (alkaline-basic rocks), other than the predominating tholeiitic basalts. Here also occur picrite members.*

A comparison of the lower strata of the terrestrial trap sequence over the entire syncline attests the fact that lavas and tuffs early in the volcanic epoch accumulated simultaneously at different places. In the east the lower strata of the volcanites of Taymyr resemble the southern sequences of the Tungus syncline, and in the west, the northern.

In the entire region, above lie basaltic sheets about 1 000 metres thick. The lavas rapidly wedge out southwards, but they have earlier been more extensive; there exist their remnants and dikes—volcanic vents. In the thicker lava units in the northwest of the syncline, more alkaline basalts, trachybasalts, occur at the base and in the middle of the pile. There also occur lava blankets similar to picrites. The total thickness of the series exceeds here 2 kilometres.

In the northeast of the syncline, specific ultrabasic rocks containing much alkalis are present along with one kilometre of basalts overlying the tuffs. They occupy the lowermost and uppermost parts of the lava sequence. The upper-

* Basic lavas containing much magnesium.



most lavas are ultrabasic proper, with high magnesium and low silica contents. Their large volumes are known only here (Maymecha River). According to L.S. Egorov, they are more than 2 kilometres thick. This is a specific area of the trap field, where the magma rose from the greatest depths. The upper alkaline and ultrabasic lavas with thin tuff interbeds made up in the past a shield-like superstructure over the blanket of omnipresent tholeiitic basalts. Dikes of such rocks are known also along the northern margin of the syncline. The earlier shield volcanoes has now eroded, only their stumps have been preserved.

In Taymyr, the thickness of common tholeiitic basalts exceeds 2 kilometres. According to G. A. Kovaleva, here at top also lie alkaline lavas that made up shield volcanoes.

The accumulation of the tuffaceous pile exhibits a tendency common to far-distant places. This contradicts conceptions that the material was distributed around the local major volcanic centres. The striking proof is the stratification of the tuffaceous pile—subdivision into non-coeval parts with the systematic changes in the thickness of all horizons over the area. A comparison of the sections indicates a constant increase in the thickness of all the distinguished units from the south, the Angara River basin, to the north, towards the centre of the Tungus syncline. The lowermost and uppermost strata show graded bedding, indicating large water bodies at the time of their accumulation. Ancient fish and gastropods, whose imprints were found in the tuffs, show that the water in the basins was brackish, as in lagoons. The flora remains as well as pollen and spores of terrestrial plants were redeposited in the water. This points to the fact that water basins are shallow and parts of land are protruding.

The radical distinction between the tuffaceous unit in the traps of the Tungus syncline and the tuffaceous series of the modern areas of volcanism has made A.A. Menyaylov, a

Fig. 3. Schematic map of the trap province of the Tungus syncline and Taymyr:

1—post-trap sedimentary cover; 2—lavas (a—tholeiitic basalt, alkali basalt, ultrabasic lavas; b—only tholeiitic basalt); 3—tuffs; 4—zones of intrusion clustering in sediments beneath traps; 5—trap-underlying sediments of the sedimentary cover; 6—salients of the basement (I—North Taymyr; II—Anabar anticline; III—Enisei Ridge); 7—ultrabasic-alkaline rocks (a—plutons with carbonatites, b—kimberlite pipes); 8—arcuate and ring dikes

volcanologist, completely negate a magmatic origin of the Tungus tuffs and propose their formation from sedimentary rocks by means of alteration by deep-seated solutions. Although this conclusion seems to be unfounded the underlying facts are worth mentioning.

As has been said before, the tuffaceous unit is composed of persistent beds. The magmatic character of the bulk of material casts no doubt. It consists of volcanic bombs, as large as 30-50 cm, showing cooling zonation; lapilli, small vesicular volcanic bombs as large as walnut; and gravel- and sand-size beads of vesicular or massive volcanic glass—solidified and non-crystallized magma. At the same time, the wide range of the grain-size composition, the roundedness, and sorting material, and the varying amount of sedimentary admixture in the form of large and small fragments vary quite sharply in non-coeval beds. The tuff sequence does not resemble the diverse volcanic series of modern volcanic terrain; it more looks like a sedimentary cover with difference in strata generally due to the different types of material introduced into the depositional basin in various time intervals.

That the thin volcanogenic members are persistent over areas of tens of thousands of square kilometres indicates that the surface of sedimentation was remarkably smooth. The downwarping of some areas was gradual, with amplitudes as large as 100 m, but it left behind the introduction of volcanic products. Non-cemented material was redeposited in the deepening basins. The minor strata displacement were frequently accompanied by dike intrusions, which indicates roof caving above the emptied near-surface magma chambers (caldera-like subsidence)

There can be suggested the following general changes in the mode of volcanic activity in the area: (1) outbursts of ash tuff; (2) outbursts of ash and coarser tuffs, redeposition of the erupted material; (3) magnificent explosions ejecting coarse tuffs, xenoliths of deep-seated rocks, fragments of sediments, and basaltic bombs; (4) outbursts of ashes and violent relict explosions with the formation of bomb beds alternating with redeposited sediments.

The above traits of explosive trap volcanism show that it cannot be compared with that of modern active areas on Earth. The identical structure of thin formations indicates material supply from small, identical, but numerous explo-

sion centres acting either for a short time or instantaneously.

A comparison of trap paleovolcanic regions with the modern areas of volcanic terrain, based on the principle of uniformitarianism, points to a tempting way of restoring the previous volcanic landscape by ascribing to it the features of the present-day one. Since the zones of today's volcanism known in mountainous regions embrace huge conic edifices, it was considered that areas of tuff accumulation in the trap terrain must also have contained magnificent cones. The inferred major volcanoes with their thick vents, inclined series of bulk cones, and the concentric distribution of the erupted material were sought for in trap fields. Minor fissures filled in with tuffaceous material (tuff dikes) were attributed to Neptune without any hesitation. They were thought to be filled with sediments precipitated from water. However, the cross-section of the dikes (isometric pipes are much scarcer) that cut through flat-lying tuffs (Fig. 4) shows that they can be regarded as explosion conduits through which the material was thrown out of magma chambers. All dikes are filled in with (1) lava, (2) lava and tuff breccia, (3) tuffs that are either coarser or finer than the enclosing rock, (4) simultaneously lava, tuffs, and xenoliths of the underlying sedimentary rocks, and (5) only small and large blocks and even wedges of the underlying sedimentary rocks. The spectrum of relationships inside the cross-cutting dikes points to their genetic affinity. They are links, so to speak, of one chain. Since the end member of the series is dikes through which lava is extruded onto the surface, they reflect a distinct connection with magma chambers. The difference between the members of this series of explosive bodies is that the conduits filled in with tuffs and fragments were not later used by pouring-out melts.

N.L. Sapronov, a geologist, gives the name linear volcano-structures to dike systems of one of the regions of the tuff field of the Tungus syncline (Podkamennaya Tunguska River basin). Their characteristic feature is a random arrangement of small volcanic vents on the dike. Such dikes with pipes (vents) extend from 10-15 to 150 m, rarely to 300 m. In plan, they are undulating, arcuate, or irregular. These arcuate channels — conduits of explosive material — are younger than central vents; they were later used by lavas quitting the Earth's interior. In some places the lavas fill in the

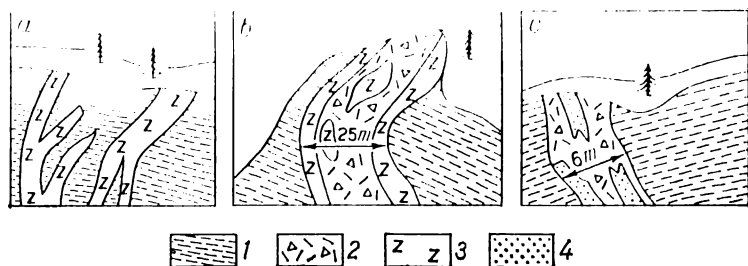


Fig 4. Dikes—channels along which tuffs and lavas rise to the surface;

a—lava-filled; *b*—filled with lava, tuffs, and rock blocks; *c*—filled with tuffs and fragments of underlying sedimentary rocks; *L*—bedded tuffs; *2*— coarse-clastic tuffs; *3*—lava in dikes and in the form of bombs in tuffs; *4*—blocks of sedimentary rocks

channels, and swells of coarse xenotuff are preserved above channels-dikes. Short straight linear faults that served as conduits for tuffs and lavas are regarded as the youngest.

The presence of major volcanic edifices within the syncline cannot be ruled out. Volcanic vents are known in the Angara-Ilim region. They are located outside the trap blanket, extend through Paleozoic sediments, and are as large as $2\,400 \times 700$ m. According to the geologists M.K. Ivanov, T. K. Ivanova large volcanoes occur in the Noril'sk region. However, the existence of such edifices in the central areas of the syncline requires better founded proofs than were given before.

The contacts of large cross-cutting pipe-shaped bodies within the enclosing tuff strata must look at exposures no more than blocks with tuff series of various types. Such zones, sometimes with an intricate interface, are common and are usually complicated by intrusive traps. It is no easy matter, however, to treat the blocks made up of unsorted explosive breccias as the vent facies. The roof of near-surface magma chambers subsided possibly due to a removal of magma and volatiles through numerous cracks. Most probably, the tuffaceous unit of the Siberian traps owes its origin to such fractures.

Where the lavas lie on crystalline basement projections not covered by sediments, trap sills become atypical and intricately shaped intrusions are also scarce. Narrow and rare dolerite dikes predominate here.

The orientation of dikes in plan is clearly shown on geological maps in zones where the continuous lava blanket is eroded. It is practically seen on any geological map that the dikes are invariably clustered in the Tungus syncline either along concentric fault systems penetrating from shallow depths, or along radial faults with respect to the concentric ones. The number of such systems varies. Such "laces" of dike swarms are known to be the densest within the outcrops of tuffaceous members lying beneath the lavas or of the uppermost coal-bearing series. Deeper in the section, these "laces" of vents are becoming less dense.

By analyzing carefully the shape of trap intrusions, the Leningrad geologists E.S. Kuteynikov and N.S. Kuteynikova have shown that these frequently build up ring structures whose topographic expression is either closed or crescent-shaped swells. On small-scale maps, as if we view them from a distance, the swells frequently appear as regular rings, although in detail they are polygonal, ellipsoid, or pear-shaped. Some of them have rectangular or rhomboid delineations. Central depressions are inside the swells.

Multiple superposition of ring features is frequently observed, the smaller one overlapping the larger. There are paired structures touching one another; a segment of their ring is common. The ring structures are 5 to 120 km, most frequently 15 to 35 km in diameter. Crescent-shaped segments occur whose curvature radius is 70-80 km. The largest rings, 60 to 120 km in diameter, predominate on the eastern margin of the syncline.

N. L. Sapronov considers ring dikes to be roots of paleovolcanoes. Many of them are composed of clastic (tuff) material. Some of them have one focus, others several foci, their diameters ranging from 0.8 to 12; 25 to 65; and 80 to 175 kilometres.

E. S. Kuteynikov and N. S. Kuteynikova believe that the rims overlain by a tuff and lava blanket are responsible for the fact that the situation in the Tungus syncline resembles the margins of lunar maria.

At the same time, the margins of many trap blankets exhibit distinct systems of uniformly oriented dikes extending for great distances. Such systems of dike fields are frequently seen along flexures, that is along zones of steeply inclined lava blankets, in areas of the thickest lava complexes (the

east of Greenland, the Lebombo flexure of South Africa, the flexure of the West Coast of Hindustan, etc.).

Such dike "swarms" with distinct northwest and northeast trends are also known on the margin of the lava blanket of the Tungus syncline, along the slopes of the Anabar uplift. They are a characteristic element of the internal structure of the trap blanket. These dike swarms are frequently treated by the students of separate localities in trap fields as the main conduits for lavas forming the basic blanket, although they usually serve for the rise of the magma of the youngest shield and central volcanoes.

The above "laces" of variously oriented dike systems are *omnipresent* in trap provinces. It is undoubtedly that the dikes serve as the main conduits for the magma pouring out onto the Earth's surface. The systems of differently oriented dike "laces" are invariably sealed with igneous rocks.

The epoch of trap volcanism began with lava extrusions in the northwest of the Tungus syncline. Piles of fragmented and crumpled underlying sandstones are frequently found at the base of thin lower sheets composed of trachybasalts, and also on the margins of lava tongues. The lavas drag, as it were, their bed. This suggests that the first outpourings took place on a slightly elevated continent. Moreover, the lowest lava sheet in the Noril'sk region is overlain by a clayey member with a coal seam formed on land. Subsequent outpourings of tholeiitic basalts occurred over huge areas at the time of gradual sinking. At times, the sea advanced from the west over the plain. Lagoon-type water bodies migrated over the area.

The basaltic sheets frequently have their base consisting of pillow lavas. Extrusions took place under submarine conditions, the lava spreading formed separate flat "pillows". In sheets, more than 15 m in thickness, such features are not known; large lava masses cooled slowly to produce uniform sheets.

An important feature of basaltic sheets is that they are surprisingly persistent. Sheets more than 20 m thick stretch for tens of kilometres without any wedging out. The melts issued to form real seas of boiling material and their depth was sometimes hundreds of metres. The thickest basaltic extrusions are typical of the close of the areal volcanism epoch.

The orientation of the lava-issuing fissures, their size at depth, and the time of their existence are not completely

known. An intricate dike pattern has been established. The dikes intersect and trend northeast, northwest, or almost east-west. The dikes mark fissures along which lava was extruded onto the surface. The upper crust was at that time very much like a finely broken plate.

Some of the fissures are directly connected with intrusions. A multitude of dikes sometimes deviate upward from a single pluton. Deep in the sedimentary layer beneath the lavas, below the principal level of intrusion occurrence, the number of small dikes diminishes sharply. Major dikes trend here more definitely. The cross-cutting, northeast trending intrusions in the west of the trap field show the orientation of deeper fissures.

The same type of lava outpourings was established in Taymyr. Early in lava accumulation, fissure outpourings predominated here as thin lava flows, which then became thicker. According to G. A. Kovaleva, the upper strata of the sequence exhibit lavas issued under submarine conditions (black shales with marine fossil fauna lie between the sheets). The latest alkaline-basaltic rock eruptions made up shield volcanoes. They first also formed in the water and then as volcanic rocks accumulated, emerged from the sea.

Thus, in the trap volcanism epoch, the depositional surface of the Tungus trap field was a lowland which from time to time submerged below sea level. The downwarping was almost all the time balanced by accumulation of volcanic rocks. The relief of the surface was smooth, which just predetermined the persistence of thin tuff layers and separate lava sheets.

The volcanic material issued onto the Earth's surface through a complex pattern of minor intersecting fissures. Some of them were directly connected with near-surface magma chambers—modern intrusive traps. The type of volcanism changed simultaneously over vast expanses.

Basaltic Melts Solidified at Depth

When geologists study intrusions, a problem of room faces them: in what way do intrusions invade sedimentary sequences?*

* The subsidence of blocks beneath major intrusions to release the room has long been discarded, because all displacements occur near the Earth's surface.

A conception was traditionally shaped up that the basaltic magma is supplied from the interior under pressure and is distributed horizontally along weakened zones in the sedimentary cover. Geological observations, however, suggest that other proposals can be put forward. Thus, P.E. Offman, one of the students of the Siberian traps, notes that the rocks that enclose dikes and stratiformed bodies do not bear traces of disturbance at the contact zone. No traces of rock fragmentation, bending, crumpling, or other deformation are observed on fissure walls. Presumably, the magma filled the already existing spaces of fissures. At the same time, previously created fissures or any other voids should end with the enclosure of the separated or broken layers, which contradicts facts (Fig. 5) indicating that the rocks of the bottom and roof at the end of spaces filled in with sills were not separated. The intermediate layers also occur beyond the stratiformed igneous bodies. The separating members abut, as it were, against the contact zone of the intrusion, "disappear" inside it and then appear again, where the intrusion wedges out. The terminations of stratified bodies are frequently intricate in outline, with small bed-by-bed bays and flowing around separate interlayers.

It can frequently be seen that a generally conformable stratiform body is cross cutting in detail. Also, some crumpling of strata in the immediate vicinity to the contact was noted. Such localities indicate an active magma intrusion. True enough, general structure is left intact; instead, the sedimentary sequence is partly destroyed by the intrusion.

Large xenoliths and blocks of sedimentary rocks inside the intrusive body retain more often than not the previous attitudes and are relics of the sedimentary unit. Upside-down blocks of rocks are sometimes found. Displaced, detached, and crumpled slabs along contacts are sometimes observed. In some cases, indications are noted of magma squeezed out of the main chamber, with the faulting and the filling of typical fissures. Such fissures pass into common crosscutting dikes, channels for lavas.

The special position of intrusive traps inside sedimentary series was also noted by Yu.M. Sheynmann. He clearly shows that the hypothesis of passive intrusion of traps is invalid. This view was later shared by V.L. Masaytis, who gave attention to the fact that all minor faults in the upper strata of the sedimentary cover die out downward, where

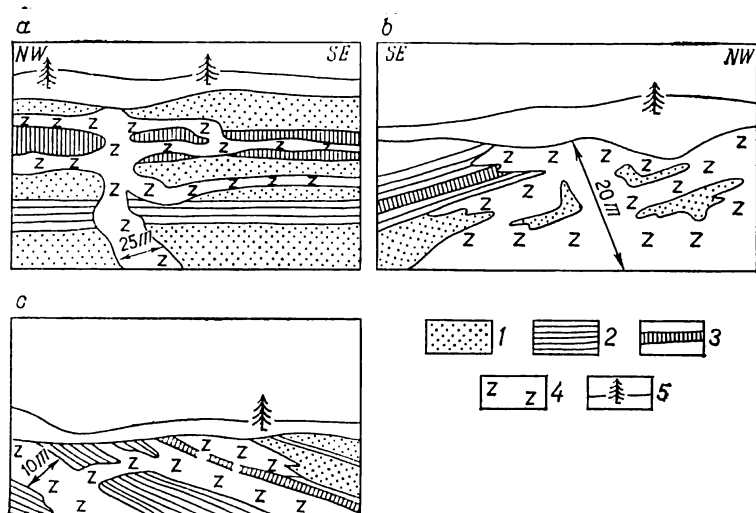


Fig 5. Relationship between intrusive traps and sedimentary rocks: *a*—right bank in the upper reaches of the Gorbiachin River; *b*—the same in the lower reaches of the Gorbiachin River; *c*—right bank of the Pokin River; 1—sandstone; 2—compact clayey rock; 3—coal; 4—intrusive traps; 5—unexposed localities

rock units are more massive. Since in some areas the igneous masses in the sedimentary cover exceed a kilometre in thickness, V. L. Masaytis assumes that the relevant space may result from major uplift of the roof. However, the persistence of thin formation of the tuffaceous sequence of terrestrial traps and the major lava sheet markers clearly contradict this assumption. If one expects the roof uplift to be related to igneous intrusion one should then assume that the intrusive bodies are formed after terrestrial trap accumulation and associate only block movements that postdate lava extrusion with magma injection. This is also difficult to accept, because the tuffaceous unit consists to a large extent of rock fragments of near-surface igneous bodies.

In each particular case, several ways of provision of space for the intrusion can be proposed, especially in areas cut by faults, but the overall absence of roof uplift in connection with trap intrusion causes no doubt. This is clearly observed on geological maps of any scale. As a result of specialized investigations, M. L. Verba has come to the conclu-

sion that generation of intrusive traps mostly implies replacement. The role of ploughing up the magma chambers by explosions, with sedimentary rock blocks thrown out onto the surface (Yu. M. Sheynmann's suggestions) appears to be also significant. This mechanism cannot, however, be responsible for the phenomenon of availability of space both for large uniform massifs, on the one hand, and small trap bodies of intricate shape, on the other. In trying to explain these facts, one should assume the formation of an intrusive trap with an extensive incorporation of the sedimentary unit. For instance, I.A. Rezanov and I.A. Zotov come to the conclusion that three fourths of traps by volume form at the expense of the enclosing strata because various gas-liquid fluids are introduced from the rising deep-seated melt into the country rock. The source of fluids is the upper mantle. This process was called metamagmatic replacement (D. S. Korzhinskiy's term, an Academician).

Other authors also apply the hypothesis of magmatic replacement to stratified intrusions. The famous Bushveld pluton in Africa, which has long attracted attention to the problem of space for basic rocks, is also under study in terms of magmatic replacement. S. Biljon shows the conversion of sedimentary rocks into igneous rocks with the preservation of initial structural and lithological zoning of the surrounding strata. In his opinion, the zoning of the pluton reflects the structure of the enclosing rock.

The most complex in this problem is the fact that rocks of subsurface intrusions and surficial extrusions of trap provinces are identical in chemical composition. The composition of material formed in the chamber due to magmatic replacement is identical to that extruded onto the surface.

An important aspect of the structural setting of trap intrusions is their apparent concentration immediately below lavas, in the uppermost strata. For instance, intrusions of the Tungus syncline are most numerous in a coal-bearing unit underlying the lava pile. Calculations of intrusions made in recent years have shown that 60 to 90% of all trap intrusions occur just here, totalling 70% by volume. Below 1.5-2 kilometres only 20 to 30% of sections are built up of sills. Scarce intrusions, or even their absence, were found deeper. In still deeper strata, the number of plutons reduces, dikes prevail instead. The number of the latter again sharply decreases with depth, until they disappear in some

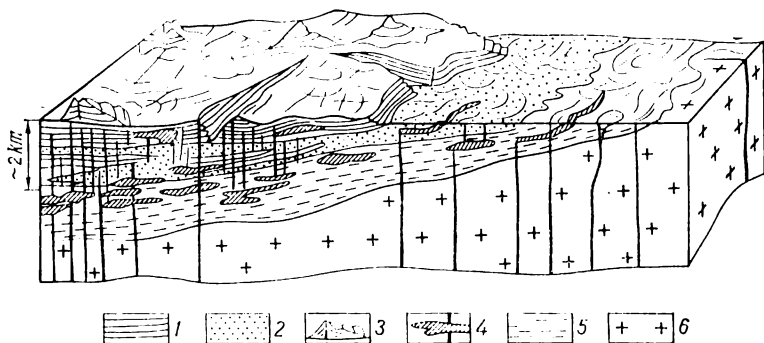


Fig. 6. Block-diagram of trap occurrence:

1—basaltic lavas; 2—tuffs; 3—volcanic shields of the superstructure complex, 4—intrusive bodies and dikes—channels for rise of magmatic melt; 5—sedimentary cover; 6—basement of the platform

zones. The intrusions always occur in a sedimentary unit 2 to 3 kilometres thick, lying below the lavas.

On a block-diagram showing the key structure of the trap complex and its relationships with the underlying strata, this complex is something like a basaltic roof above sedimentary strata (Fig. 6). It can be compared to thick tops of trees in a wood, these tops almost completely covering the sky, with only trunks below. The arrangement of traps in the Earth's crust can be compared to a mushroom colony on a stump. All their caps merge and partly overlap one another to form a continuous slab, multistory to some extent, while their thin stems under the layer of mushroom caps are merely vertical threads rising from the spawn.

It is still difficult to judge upon the shape and size of the trap source deep in the Earth. The presence of cracks sealed with magma, however, by no means proves *pushing aside* crustal blocks of similar scale. Reasoning that the occurrence of a lava blanket is always a feature of breaking and pushing apart the Earth's crust, which is many kilometres thick, has no foundation. Few and thin conduits exist in the lower sedimentary strata and the basement. Magma rose along them from the Earth's interior as through a water main, and the result was an extensive lava reservoir at the surface.

Basaltic Seas on Terrestrial Ocean Floors

Being obscured by water, the floor of the World Ocean cannot be observed directly. One can judge upon the structure of the lava blanket on the floor by studying rock fragments dredged from great depths, where the solid floor displays rock outcrops. The upper strata of oceanic rocks owe the origin to deposited muds transformed into sedimentary rocks. They are underlain by basaltic lavas, solidified melts. It is the basaltic blanket that is called the ocean floor bedrock.

Scarps of solid rocks usually form in areas where the Earth's crust is cut by faults. Usually, the crust is vertically displaced along a fault, and one of its sides is elevated relative to the other. There are very many scarps of this kind in the ocean floor bedrock. Their distribution and relationships with other topographic forms of the floor will be discussed below; here we shall describe the ocean floor layer overlain by sediments.

The deposition of the sedimentary layer on the ocean floor is determined by its topography, specifically depth contrasts rather than absolute depths. A small amount of sediments accumulate on the crests of highs and on their upper slopes. More sediment is laid down at the base of slopes and in closed basins. What is called depositional velocity inversion arises where the sedimentary cover forms more rapidly at shallow depths. This is the case if carbonate rocks accumulate more actively in the warm ocean water on submarine rises better lighted and heated. At the great depth, at low temperatures and under the pressure of the ocean water, the carbonate matter dissolves and only clayey sediments can pile up. The level at which carbonates dissolve is called the critical depth of carbonate precipitation. Evidence is available that this level changes with geological time.

Investigations of the past 15-20 years have revealed that the sedimentary cover is quite irregular in thickness on the surface of bedrocks. Deep currents and landslides play an important role in the transport of material under water. The material flows down the slope, and as a result of it bedrock exposures appear in scarps and ridges on the ocean floor.

The Soviet investigators G.B. Udintsev, P.L. Bezrukov, and N. M. Chernysheva as well as the American scientists H. Menard, A. Engel, and C. Engel have made much to improve the knowledge of the Pacific floor bedrock by studying dredge hauls.

The bedrock dredged consecutively from different depths of a scarp of the ocean floor may tell us about vertical rock distribution in the section of the exposed slope. The scarps along faults are relatively elevated to a maximum height of 4 kilometres, rarely, to a greater height. Along deep trenches in the margins of the Pacific Ocean, the crustal section is exposed, though discontinuously, to a depth of 10 kilometres. Dredging results thus provide a very important clue to the structure of the seabed to large depths.

Fragments of igneous rocks, even very large ones, chipped off submarine cracks may tell us about rock composition, the type of melt, and how the magma solidified. It is impossible, however, to perceive from the fragments what the structure of igneous bodies is, what underlying and overlying units are, and in what zones these bodies can be divided.

Principally new information about the structure of the magmatic floor under the sedimentary cover can be obtained from deep-sea drilling.

The first deep-sea test borehole was drilled in 1964 by the American geologists in the Guadeloupe Island area of the Pacific. Four years later, several holes constituted a section from the Florida coast to the underwater Blake Plateau. In conformity with the International programme *Deep-Sea Drilling*, the first borehole was drilled in 1968 in the Gulf of Mexico. Since 1974 the USSR has been a participant of this programme.

Drilling is made from the special American vessel *Glo-mar Challenger* which handles more than 7 kilometres of steel drill string. More than 500 holes have been drilled in the World Ocean; in most of the holes, the sedimentary layer was drilled through and the drilling bits penetrate directly into rigid basaltic rocks of the ocean floor. Since drilling is conducted at the open sea with the average depth of 5 kilometres, it is impossible to use anchors to position the vessel. It is kept above one point with the help of a special sonar beacon. An electronic system provides vessel positioning, automatically commanding the screws and thrusters even

during violent storms. Because drilling is very expensive, each drilling site is chosen carefully with due account of all the data available.

It should be noted that the drill string can enter the basalt of the ocean floor only if at least 100 metres of sediment lies above it. Only such a unit, which can be drilled easily, may serve later as "rails" for the bit pushed into the more compact rock of the floor.

Drill pipes can now be again introduced into a hole in the ocean floor to continue drilling after replacing the worn bit. In 1981 the first experiment was carried out to re-enter a borehole suspended for 5 years and again examine its hole by special geophysical instruments.

The greatest depth to which the ocean floor basalts were drilled is 550 metres. This is Hole 395 of *Challenger* Cruise 45, located in the central part of the Atlantic Ocean. Most other boreholes penetrated into basalts to shallow depths and thus only the topmost part of the lava blanket that covers the floor. This is because basalts are very hard rocks as compared with the overlying sedimentary strata. Flint interbeds, which frequently lie above lavas in the ocean, are hard or even harder than basalts. Fortunately enough, even a small basalt section may tell us about the mean thickness of lava sheets and the mode of alternation with other rocks.

The Soviet specialists invariably participate in oceanic bedrock studies. Among the Soviet petrologists that contributed much to the knowledge of types of oceanic igneous rocks and their origins are L.V. Dmitriev, B.P. Zolotarev, S.I. Shcheka, I.O. Murdmaa, N.A. Kurentsova, A.I. Sharas'kin, Yu.I. Dmitriev, L.I. Kashintsev, and D.A. Frikh-Khar.

Because the ocean floor basalts are everywhere overlain by sediment and even where they are exposed they are covered by the ocean water, one can judge upon the structure of the lava sequence only from dredge hauls or from core samples. To compare the sequences of the basaltic blanket of the ocean with those of the lava units on the continents, it is desirable that boreholes be spaced very closely so one could find now rapidly the structure of units changes along the strike. It should be said that at present the spacing of holes is large, the closest boreholes being commonly spaced at hundred of kilometres.

Two holes drilled during *Challenger* Cruise 51 at the southern termination of the Bermuda Rise are, however, spaced only at 450 metres. These are Holes 417A and 417B, and the ocean is here 5 468 and 5 482 metres deep, respectively. The first hole penetrated 417 metres of ocean floor rocks of which 206 metres were run through basalts. The second hole drilled through 532.5 metres of rock, of which 189.5 metres were bedrock basalts.

Hole 417A has shown that the lava sequence is composed of five basaltic flows with the pillowed surface, their mean thickness varying between 20 and 80 metres. The lava flows are separated by lava breccias, that is fragments of the same lavas filling up interstices between the rounded rises of tops of basaltic sheets or between isolated lava pillows. A thin layer—an intrusive body with a denser crystalline structure and without pillows—lies among the sheets whose magma spread and form pillows. The central part of the pillows and the median zones of the flows are made up of dark-grey hard basalts with large lighter plagioclase phenocrysts.

The lavas underlie brown clay of Late Cretaceous age. Altered basalt fragments 2 to 6 centimetres and smaller in size rest on the surface of the uppermost sheet, that is at the top of the lava sequence. Their shape suggests that they are derived from basalts disrupted in shallow water. The basalts of the upper sheets are severely altered by weathering which is usually typical of continental lavas. These changes in the once dense basalts have converted them into a grey-brown, easily mashed mass with relics of large crystals of light plagioclase. Examination under the microscope has shown that the fresh rock is a rapidly solidified magma that contains still non-crystallized volcanic glass along with large plagioclase grains. The rock was altered after a complete solidification of the melt; as a result, it was enriched in potassium and impoverished in silica and calcium. Deeper in the lava unit, secondary transformations are becoming weaker. But a greyish-brown colour instead of dark-grey one is noted on the margins of pillows.

In Hole 417B, black clay of Early Cretaceous age lies above a lava unit resembling that in Hole 417A. It is overlain by brown clay similar to that in the roof of the lavas at the previous site. Thus, the lavas in the neighbouring boreholes are overlain by clays of different ages, though they them-

selves are clearly similar and undoubtedly extend in the seabed from one drilling site to the other. Here, the lava unit is composed of 15 minor flows which also exhibit pillows. There also occur sills, intrusive dolerite bodies. Basalts are here much less altered.

The lava unit drilled through by boreholes and consisting of thin sheets is comparable with certain formations or members of basalts in trap provinces, where they accumulated as a result of minor outpourings alternating with tuff outbursts. It is in such formations that one can observe rapid changes in the amounts and thicknesses of extrusive horizons and intervening tuff layers.

The lava breccias intercalating lava sheets are similar to the material in interstices between the pillows of minor lava flows of continental traps.

Pebbles on the surface of sheets, the red surface of pillow lavas as a result of weathering, which indicates the presence of iron oxides in the weathering crust, all this suggests that the lavas were altered either above sea level or in shallow water. It is interesting that the lava blanket began to subside very slowly and differentially only after lava accumulation. When clay had accumulated on the lava surface at site 417B, the neighbouring locality was still elevated, and the lava was under weathering until it subsided and was overlain by younger strata, that is much later.

It is clear that the lava unit was a shallow-water near-shore zone after its accumulation at least for several million years (about 100 million years ago). Clayey muds accumulated only in some topographic lows. The subdued relief of the lava terrain and the shallow sea that covered it were similar to those in trap provinces. And the whole area subsided to a great depth of 5.5 kilometres much later.

Hole 524 (*Challenger* Cruise 73), east of the Walvis Ridge, also ran into a rather old basaltic sheet overlain by Late Cretaceous sediments. At the very bottom of the hole, 340 metres below its head, located on the ocean floor at a depth of 4 796 metres a sequence of lava sheets and minor sills occur totalling about 20 metres in thickness and intercalated with volcanogenic and clastic (tuff-like) strata. This unit of igneous layers is not considered a true basaltic basement, which, according to geophysical data, lies still deeper, approximately at 6 kilometres. However, with its lava layers intercalated with sills and tuffs, it has the same fabrics as

the lava members of trap provinces. Upwards in the section of this borehole, the volcanogenic and clastic rocks also contain several thin basaltic lava interbeds. This underscores the fact that volcanism is dying out gradually, and some impulses of melt penetration to the surface take place after the formation of a unit of stratified sheets.

An example of a lava blanket section in the young marginal sea floor of the western Pacific is afforded by Hole 447A, located in the east of the West Philippine Basin. Here, deep-sea clay and an ash tuff bed are underlain by a thick (182 metres) member of several alternating basalts some of which are massive and the others are pillowed. These lavas make up superposed sheets. They are indistinguishable in the composition of melt and the appearance of extrusive rocks from typical tholeiitic basalts of other parts of the ocean floor.

Most deep-sea boreholes were shut down once they had entered basalts because of drilling troubles. Penetrated usually are 1 to 2 metres of the lava top or clasts of basaltic composition, of which the rock is full, much more seldom, first few tens of metres; even then, however, they provide some information about basalts in the ocean floor.

Hole 205 (South Fiji Basin, Cruise 26), located at a water depth of 4 320 metres, penetrated about 10 metres of uniform massive basalts with plagioclase phenocrysts at a depth of 345 metres below its head, under Oligocene carbonate mud. It is quite possible that this is a major sheet. The overlying sedimentary layer contains a cross-cutting body, apparently the margin of a dolerite dike, which may also intrude the lower sheet. Near the dike, carbonate fossils are recrystallized, which suggests contact effects of the solidifying melt. Here, the upper part of a lava blanket that has higher lava horizons in the adjacent areas was apparently penetrated. The cross-cutting dikes may have been their vents.

Hole 167 (Cruise 27, Central Pacific Basin, the northern flank of the Magellan Rise, water depth 3 176 metres) was drilled through a basalt member, 12 metres thick, which lies below Late Jurassic limestones and siliceous shales at a depth of about 1 200 metres from the hole head. The rocks are severely weathered and veined by calcite; the basalts are at places brecciated, which suggests, not one sheet but several thin superposed sheets intercalated with tuff breccia. The lower part of the unit is very microcrystalline. The upper part of the basalt member contains plagioclase pheno

crysts. Textural differences also point to several consecutively solidified lava flows.

Hole 57 (Cruise 6, the northern flank of the Caroline Rise, water depth 3 300 metres) penetrated the contact of chalk with an igneous body at 335 metres below the hole head. The contact is irregular, which may indicate magma intrusion and then the body should be regarded as a sill. This seems to be confirmed by good rock crystallinity, not typical of rapidly cooling glassy lavas. No contact alteration is present, however, which means rather, that the hole penetrated the top of a thick sheet. In trap provinces, such sheets, more than 20 metres thick, consist of holocrystalline basalts indistinguishable from intrusive materials.

Hole 155 (Cruise 6, the east of the Pacific, near the Panama Isthmus, water depth 2 752 metres) was drilled through a 17-metre basalt member underlying Miocene carbonate mud. The basalt is holocrystalline and slightly weathered under conditions of oxygen deficiency. There are minor sheets intercalated with clastic carbonates without contact alteration. It seems that these basalt flows solidified under water.

Hole 304 (Cruise 32, southeast of Japan, water depth 5 630 metres) entered basalts underlying a 334-metre unit of carbonate muds with siliceous lenses of Cretaceous age and penetrated it to a depth of 13 metres. The basalts of different flows are crystallized and weathered to different degrees. Large plagioclase and dark pyroxene phenocrysts have been found in some layers, in others have not. This suggests several alternating lava bodies. Another confirmation is fragments of sedimentary rocks with traces of underwater living activity inside the basalt member.

Hole 257 (Cruise 26, Worton Basin, Indian Ocean, water depth 5 278 metres first penetrated a clay and chalk unit of Cretaceous age, 260 metres thick, and then a 64-metre basalt member. The basalts are medium grained, contain olivine, and make up seven or eight sheets, some of them being very thin. The upper flows are cut by fractures associated with submarine solidification. There occur thin sedimentary interbeds accumulated in periods between lava eruptions. Some of the flows are well crystallized, with large plagioclase phenocrysts. Each flow displays a vertical zoning; coarse-grained varieties with olivine tend to occur at the base of flows. Rocks also contain altered volcanic glass, which indicates that the melt is crystallized rapidly.

The top of the basaltic blankets that cover the ocean floor shows that lava sheets overlain by non-coeval sediments and located in the different parts of the ocean floor have some in common. All of them, major or minor, intercalated with sediments or tuffaceous beds, were emplaced onto the land surface or in a very shallow sea so the top of sheets underwent weathering or wave action. All lava units, together with their substratum, were submerged to great depths much later under the ocean water.

The lava members intercalated with sediments or consisting of alternating flows are structurally the same as the lava blankets of trap provinces. None of the specific structural features of the lava members indicate that the mode of accumulation of extrusive and explosive rocks on the present-day ocean floor was other than that in the plateau-basalt provinces of continent.

We emphasize this because there is a widely accepted opinion of a specific type of accumulation of oceanic basalts, namely that they actually issue from a single expanding fissure. Such a fissure is assumed to occur in the median zone of a mid-oceanic ridge. When a lava surge passes through the fissure from the Earth's interior, it solidifies at the edges of the fissure, which thus becomes sealed. Then a new lava surge invades through the median zone of the fissure, which again becomes sealed at its edges, this process being accompanied by pushing apart its walls and crustal blocks. These huge crustal blocks are called lithospheric plates, consisting of continental masses with the parts of the ocean that lie on either side of the mid-oceanic fracture. According to this concept, the lava unit in the ocean floor is composed in its lower part of consolidated basalt dikes attached one to the other and in its upper part of a fir-tree of lava sheets that make up a succession deviating from the dike swarm.

It is supposed that such a simultaneous accretion at initial fissures in the floor inside all of the oceans on Earth has been going on since the beginning of the Mesozoic to the present. The initial master fissures in the oceans are considered to be rift zones of mid-oceanic ridges.

Even the above examples describing the structure of the top of basaltic blankets in the oceans indicate that the real relationships of the superposed basaltic flows to small vents (dikes) are the same as on continents. The presence of younger sills enclosed in lavas shows that local magma penet-

ration took place from the interior everywhere in the oceans throughout the formation of lava blankets up to the moment of top accumulation and even after lava emplacement and sediment deposition. Magma chambers beneath the area of oceanic lava blankets formation were as numerous as in the interior of trap provinces. The amount of melt from many chambers and the chemical composition of melts were responsible for those differences in thickness and structure of individual sheets that were found by deep-sea drilling.

The proponents of "pushing apart the lithospheric plates" take into account also the presence of younger volcanic mountains above the lava blanket. It is believed that parts of the floor formed in the initial parent cleft of the rift "ride" together with the whole basaltic slab over definite "hot spots" that are stationary and occur at depth. From time to time, magma "shoots through" the slab from there by way of a volcanic explosion. It comes out that the activity of the Earth's interior beneath the oceanic lithosphere practically ceases after the active area is moved away from mid-oceanic rift zone. However, the constant presence of intrusive bodies in the upper beds of oceanic lava blankets suggests that each area in the ocean was above a "hot spot" from the beginning to the end of emplacement of the main lava blanket. Along certain zones of deep-seated faults the Earth's interior remained active even much later. It is here that archipelagos of volcanic islands and seamounts rose.

That the internal structure of the volcanic blanket in the ocean floor is similar to that of trap blankets on continents points out that in the ocean the magma also most probably penetrated to the surface through an intricate pattern of numerous small conduits above local shallow magma chambers. As on continents, the connection of these chambers with deep-seated magma sources must have been maintained throughout the volcanic rock accumulation epoch.

Deep-sea drilling has also provided information on the occurrence of intrusions in sedimentary strata. This information is very interesting for comparing with the attitude of intrusive bodies in sedimentary beds beneath trap blankets. The case in point is the boreholes of Cruise 64; their sites are near the rift zone of the East-Pacific Rise off the Baja of California. Here, four boreholes (477, 477A, 478, and 481A) were drilled through very young, late Quaternary deposits

The holes ran into sills at different depths. The lowest sill is more than 120 metres thick and was not penetrated to the full. Thin intrusions upward in the section are present in some holes and absent from others. However, the total thickness of the unit remains unchanged. The American geologists believe that the intrusions do not deform the sedimentary unit but make certain compaction of the enclosing humid deposits. If one neglects this influence, the physical parameters of sedimentary strata are the same as those in the neighbouring boreholes, which encountered no intrusive bodies. According to their hypothesis, the solution of the "space problem" amounts to the assumption that the invading red-hot magma vaporizes from the deposit just the same volume of pore water that is necessary for the sill to intrude. Hence, it is injected without the rise of the overlying strata and subsidence of the underlying strata. The water driven off by the red-hot magma gives rise to hydrothermal activity; hot water transports upward material, which then precipitates on the floor.

Speaking of the space problem with respect to intrusive traps (see above), which are "inserted" in the framework of the enclosing rocks without disturbance of their bedding, we took into account the intrusions lying under the lava units. But the case in point is bodies that rest on the lava units. However, the essence of the phenomenon is the same.

Volcanic Rises on the Basaltic Ocean Floor

Large shield volcanoes overlooking the ocean water as islands, as well as isolated cones of volcanic seamounts, are common in the oceans. Both are usually restricted to fracture zones, which are represented either by rift clefts (troughs) or by elevated ridges frequently bounded by straight-line scraps.

The fabrics of volcanic superstructures rising above the basaltic ocean floor covered by a sedimentary layer is well known because, unlike bedrock lavas, they are accessible for study.

The Hawaiian volcanic edifice—a system of islands—is best known. The chain of the Hawaiian Islands lies on a wide arch of bedrock basalt, about 1 000 kilometres wide

and about 2 000 kilometres long. The volcanic chain is composed of eight large and 39 small islands on which lie, as on shallow-water shoals in-between, reef complexes. The submarine base of the ridge is made up of tens of overlapping shield volcanoes. Active volcanoes are known only on the Hawaiian Islands, Mauna Kea being the highest (4 170 metres). The size and height of the volcanoes diminish north-westward.

The lavas that build up the base of Hawaii issued from systems of fissures and were composed of tholeiitic basalts differing insignificantly from the main type of basalts of the ocean floor. The basalt sheets are intercalated with tuffs erupted from fissure volcanoes. Younger volcanic cones poured out alkaline-basic lavas of the type of trachybasalt and trachytic, phonolite lavas, which are even more alkaline (intermediate in silica content).

After volcanism had become somewhat less active, coral reefs began to form on a number of islands destroyed by waves. As the ocean floor was subsiding, coral structures grew so that the living colonies existed all the time at shallow depths. Finally, highest-alkali lavas continue to issue from some volcanoes.

Another huge volcanic rise in the Pacific is the submarine, north-south-trending chain of the Emperor Ridge, recently examined by deep-sea drilling. Tholeiitic basalts, more than 360 metres thick, corresponding to magma composition to the Hawaiian tholeiitic series, lie at the base of these seamounts. Above occur thin picritic basalts similar to ultrabasic lavas. Higher in the section lie alkaline basalts (trachybasalts) as thick as 100 metres. The section is completed with basalts intermediate in composition between alkaline and tholeiitic, about 50 metres thick. High-alkaline rocks known on the Hawaiian Islands are here absent.

Interestingly, evidence for the previous existence of islands has been obtained on all underwater rises with the help of drilling. This follows from the type of rock weathering—oxidized ferruginous crusts, etc.

Volcanic islands built up of alkaline-basic rocks are known also in other oceans. Thus, in the Atlantic, these are the Fernando do Noronha Islands, Trinidad Islands, and the Tristan de Cunha Islands in the west; the Cape Verde Islands, the Azores, St. Helena Island, etc. in the east. Islands made up of alkaline-basic and alkaline lavas are

also known in the Indian Ocean (Kerguelen Islands, Mauritius, Saint Paul, and Amsterdam islands, etc.).

Magmatite rocks of other composition also compose volcanoes rising above the basaltic substratum. They are also made up of specific basaltic varieties whose characteristic feature is a relatively high silica and iron content as compared with common tholeiitic lavas. Such lavas, transitional from basic to acidic varieties, are known on the volcanoes of Iceland, where they are sometimes called icelandites. The same rock type is also known from the Ninety-east Ridge of the Indian Ocean and on the islands of the Laccadive Ridge. Finally, some islands are built up of basalts extremely rich in iron, so-called ferrobasalts. They are known in the Pacific, namely in the Galapagos and Juan de Fuca Ridges. Identical rocks have recently been found to predominate in the Daito Ridge of the Philippine Sea.

There are very many volcanic seamounts and chains straddling faults in the ocean floor. Most of them are made up of alkaline-basaltic lavas. Many of such submarine volcanoes, especially those in the Pacific (here their number is 7.5 to 10 thousands), earlier rose about sea level, were worn down by waves, and are now capped by coral reefs. Such atolls and areas are most typical of the Central Pacific Rise and the Magellan and Caroline Rises in the western Pacific. An interesting map showing the disposition of islands of different types in this ocean was compiled by the geologist N.I. Larina.

Thus volcanic islands in the ocean always rise above the main tholeiitic basalt blanket to a height of 3 to 6 kilometres. The volcanoes are usually built up of specific basalts containing much alkali. The lavas and tuffs change in composition in the course of the gradual growth of the volcanic edifice, and below it intermediate magma chambers exist for a long time, during 20 million years or more. They are entered by an alkaline-basaltic magma coming from depths exceeding 100 kilometres. In the chambers, the melt differentiates into batches of different composition. The melt separates and stratifies, and separate batches issue on to the surface.

The melts may differentiate also in those intermediate chambers where the common tholeiitic-basaltic magma, coming from a depth of about 60 kilometres, has been preserved for a longer time than usual. From such an interme-

diatic chamber, separate fractions of lavas also come to summit of the volcano. These are high-iron basalts, or those having an unusually high silica content. Their chemistry suggests that these acidic rocks are related not to granite plutons, as on the continents, but are small silica-rich portions of the voluminous basaltic magma.

What Is Concealed by Lavas Lying on the Ocean Floor?

None of the deep-sea boreholes has penetrated the basaltic blanket lying on the floor of the World Ocean and answered the question what it is lying upon.

On geophysical evidence, even more compact strata lie below the basaltic shell. They correspond to the basaltic layer and even deeper, to the upper mantle with less dense asthenospheric "pillows" beneath mid-oceanic rift systems. The basaltic blanket that corresponds to Layer 2 of the oceanic crust is, on the average, 1.5 kilometres thick. In the Atlantic its thickness is considered to be 2 to 4 kilometres.

Materials actually emerging from the basaltic blanket are exposed where the oceanic crust is cut by faults, its parts are at places elevated, and the substratum of the basaltic blanket can be observed (Fig. 7).

Very important information on the structure of the basaltic blanket of the World Ocean and its substratum was collected through dredging of the ocean floor. Significant results were obtained in Cruise 24 of the vessel *Academician Kurchatov* which examined the sides of the Eltanin fracture zone system in the Pacific. The Earth's crust is here exposed in a scarp to a depth of 5 kilometres. Amphibolite schists* crop out in the lowermost part of the section. Such rocks are usually found on the continents in areas where rocks were strongly transformed inside fold mountains. The rocks of such a type, found for the first time, indicate that the layers beneath the basalts could have undergone a prolonged and intricate geological evolution. Intrusive bodies were found lying above them, and basaltic lavas predominate in the uppermost 1.5 kilometres of the scarp.

Similar internal structure was found in the scarps of other fracture zones. Thus, *Dmitri Mendeleev* Cruise 23 was con-

* Metamorphic rocks derived from volcanic sedimentary deposits as a result of their strong heating and compaction.

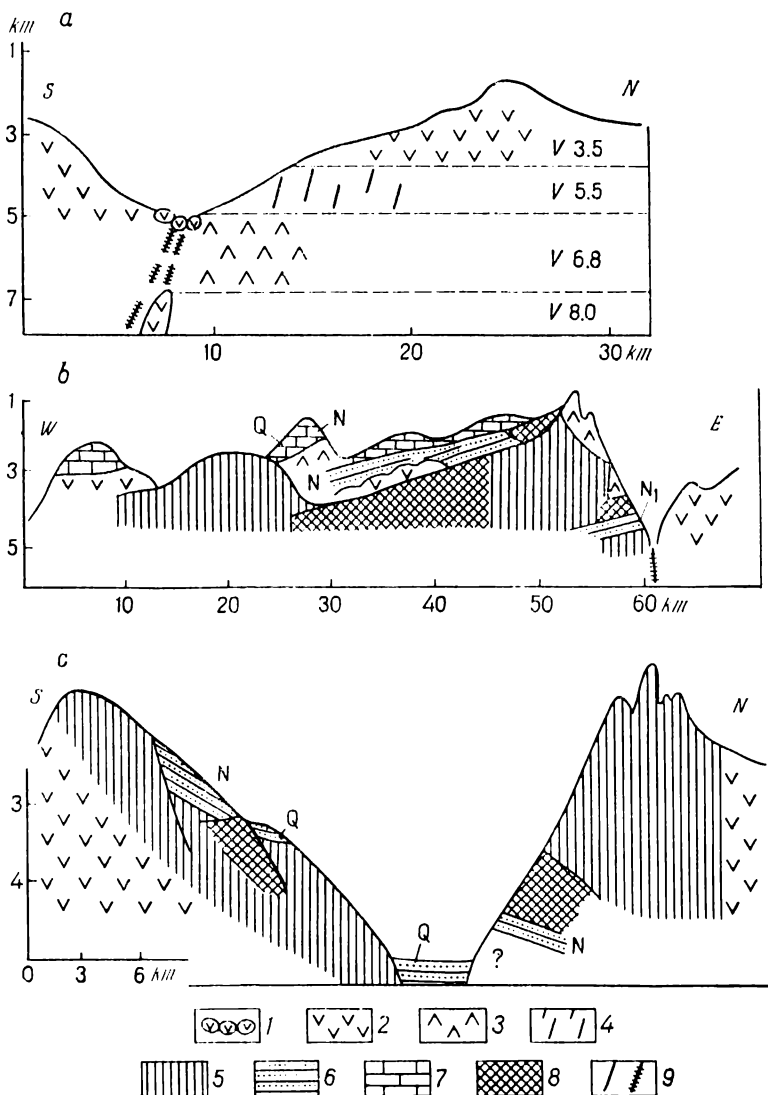


Fig. 7. Sections across scarps in the ocean floor:

a—Hess fracture zone; *b*—Atlantis fracture zone; *c*—Atlantis basin; 1—most recent pillow lavas in rifts or fractures; 2—basalts of the ocean floor; 3—intrusive bodies; 4—dikes serving as conduits for lava; 5—ultrabasic rocks similar to alpinotype rocks of continental fold mountains; 6—sediments and sedimentary breccias; 7—limestone; 8—metamorphic rocks; 9—fractures, Figures in Fig. 7a, seismic velocities, km/s

cerned with the southern scarp of the Hess Plateau in the Pacific. In the underwater wall, pillow lavas are exposed to a depth of 2 kilometres from the surface of the floor. The appearance of lava sheets indicates that lavas issued under shallow-sea conditions, and below lie intrusive rocks.

To the Emperor fracture zone that deviates from the ridge of the same name, tholeiitic basalts were dredged from the upper part of the scarp. Intrusive dolerite and gabbro are exposed down the slope of the scarp. A similar rock assemblage was dredged from the wall of the Murray fracture. Together with common tholeiitic basalts and their intrusive equivalents, ultrabasic rocks and metamorphic amphibolites have also been found here. The ultrabasic rocks varieties are seldom fresh; they are usually foliated and replaced by secondary minerals to form serpentinites.

In other oceans, a similar occurrence of the same rock varieties in the walls of submarine scarps has been established by dredging in rift zones and cross-cutting fracture zones. Whatever the origin of ultrabasic rocks and serpentinites, all their outcrops are just restricted to major fracture zones. As a rule, basalts lie on the surface of oceanic crustal blocks and below, their intrusive varieties. Together with them, or still lower, ultrabasic or metamorphic rocks emerge in the scarps. Since fractures are very common in the ocean, a great number of investigators believe that ultrabasic material occurs everywhere in the ocean floor beneath lavas and intrusions. Such a composition is regarded as typical of the Earth's mantle.

At the same time, V.M. Lavrov and M.S. Barash's investigations in the Palmer fracture zone of the Atlantic have shown that individual major scarps that mark ultrabasic rock blocks alternate in the walls of clefts with basalt blocks or with intrusive dolerite layers. The relationships among blocks are such that they can be regarded as separate scales thrust one over the other. French geologists also established intricate relationships between basic and ultrabasic rocks with their irregular occurrence in the walls of submarine scarps of the Vema fracture zone, Atlantic Ocean. These relations suggest that deep-seated layers of the oceanic crust are crumpled and compressed along rift zones of mid-oceanic ridges and along major transverse faults. Possibly, mid-oceanic and side ridges and rises had been fold zones before they were overlain by young lavas. V.M. Lavrov and M.S. Ba-

rash consider the Palmer Ridge a submarine extension of a continental fold mountain system. The interior zones of fold mountains on the continents are frequently made up of crumpled and imbricated basalts and ultrabasic rocks.

Turn now to the ocean floor section drilled through by the deepest borehole penetrating bedrock. Hole 395A, located near the Mid-Atlantic Ridge, encountered three sets of fine-grained basalt sheets. The lavas are intercalated with intrusive bodies and cut by offset zones. Basalts consist of pillow lavas, interstices between ovoids being occupied by fragments of the same composition. Ultrabasic rocks of a plutonic appearance lie beneath the upper lava unit with sharp, probably fault contact. Such rocks on the continents often build up the lower parts of the layered plutons of basic composition. Fragmented and foliated, this interbed of ultrabasic material occurs as an intruded slab, a separate scale inside the basaltic unit. The presence of sills solidified near the Earth's surface in lavas downwards in the section shows that in this case also the zone of the ridge is fold-thrust terrane. The substratum of the ridge may differ sharply from that underlying the lava blanket of the ocean floor in areas of subdued plates.

According to the petrologist S. A. Silant'ev, metamorphic rocks exposed in deep fractures in the ocean floor are identical with those in the fold structures on the continents. Metamorphic rocks are derived from sedimentary and volcanic rocks; hence, no strata of primary mantle material can underlie basalts in the ocean.

The Ukrainian geophysicists have shown that together with blocks with a high, "mantle-inherent" density, those similar in density to sedimentary rocks are present in the equatorial segment of the Mid-Atlantic Ridge. Here also, north-south linear magnetic anomalies are absent. Such direct and reverse anomalies in the north of the ocean, presumably corresponding to vertical dikes of different ages, have just led to the views of crustal "spreading" in the oceans.

Observations made by the Ukrainian scientists have also revealed that the density of the crust as a whole exhibits maxima in the transverse fracture zones of the Atlantic and Indian Oceans. This implies that the crust is here different from that of oceanic plates, areas of the seabed with subdued relief. It is in such fracture zones that ultrabasic rocks generally emerge beneath basalts. In trap provinces on the

continents, dense ultrabasic rocks also occur in appreciable amounts along faults zones. If we judged upon the materials underlying continental traps from shallow clefts along such fault zones, we could decide that the basaltic blanket (at places several kilometres thick) is everywhere underlain by ultrabasic material. The geophysicist N.K. Bulin has found a wide variety of methodological drawbacks after he critically considered the initial seismic measurements in the oceans and their treatment results, which gave rise to generally accepted views on the geophysical layers of the oceanic crust. On the latest evidence obtained by scientists from many countries, he has shown that the oceanic crust is much thicker than considered earlier. Its thickness is not 8-10 kilometres but two- or three-fold. This actually equalizes the crustal thickness beneath oceans with that of continents.

The studies conducted by V.I. Ponomarev with the help of a Soviet magnetometer used in the deepest borehole ever drilled in the ocean (Hole 495A, which penetrated more than 500 metres of basalts) have shown that the lavas in the upper and lower parts of the section are magnetized oppositely. At present, this casts doubt on the possibility of the magnetic anomalies usage in the oceans for designing any conception because it is completely unclear what objects are responsible for such anomalies. This is apparently not the basaltic layer issued through the supposed fissures at the time of spreading, since the magnetic polarity changes at the same point of the ocean along the vertical. The magnetic polarity scale—a succession of polarities of the Earth's magnetic field—loses here its geological meaning.

Important information on the internal structure of the oceanic bedrock beneath the sedimentary layer has been obtained by new L.I. Kogan's techniques. The scientist has shown that no extensive layers of different densities (geophysical layers) occur in the solid ocean floor. There occur only separate lenses of denser rocks enclosed in less dense rocks. These lenses are 2 to 7 kilometres long and 0.3 to 1 kilometre thick. They are arranged randomly, being sometimes connected in an en echelon manner. Such lenses are becoming shorter, with depth, lengths of 1.5-2 kilometres predominate. In our opinion, this pattern coincides with that of the distribution of intrusive sills and dikes that connect them in an en echelon fashion, all usually lying beneath the basaltic blankets of continental traps.

Completing the first part of the book we emphasize the principal conclusions. Observations of the occurrence of basalts on the continents and in the oceans, which together make up the outer lava shell of the planet, make us believe that in both cases the magma was supplied from the interior to the surface in the same manner. Melts penetrated from the interior through an intricate fracture pattern and poured out as red-hot sheets. The sheets superposed to form sequences totalling first few kilometres in thickness. Deeper-seated ultrabasic melts invaded along the largest faults; they frequently did not penetrate to the surface and solidified beneath the lava cover. Such ultrabasic rocks occur beneath the basaltic blankets both on the continents and in the oceans; they emerge in the elevated sides of old shear faults that cut the ocean floor.

After emplacement of the principal tholeiitic basalt blankets, again along major fault zones, specific, more often than not basic, alkali-rich, magmas rose to shallow depths. They were injected into intermediate chambers, and shield or conic volcanoes grew above the chambers over the principal basaltic blankets. On continents, such volcanoes were disrupted by erosion. On the ocean floor, being submerged, volcanic edifices over the main lava blanket rose to heights of 3 to 6 kilometres. When they grew above sea level as a result of eruption, waves truncated the summits of such islands. When the floor subsided further, the flat tops of volcanic islands were capped by coral limestone to form guyots.

When basaltic melts penetrated all the way to the surface, continental areas invariably subsided following lava accumulation and frequently sank below sea level. When lava flows were erupted one after the other on the oceanic (unknown) substratum, the contemporary seabed also subsided, though there were no such great depths as now. Uplift of the accumulated lava blankets on the continents or their subsidence in the oceans are younger phenomena. The ancient ocean floor may also then rise. For instance, the part of the former ocean floor in the area of Iceland is now again above sea level. Here, a lava blanket makes up an emergent plateau.

The question of whether or not there are actual differences in the mode of supply and surface accumulation of basalt

blankets on the continents and in the oceans should be answered negatively. The distinction lies only in their present-day occurrence.

The Age of Terrestrial Basalts and Their Relationships with Different Structures

The Age of Trap Seas on the Continents

Like ocean floor lavas, continental trap blankets are also of different ages in the different parts of the superficial basaltic shell of the Earth. That traps are of varying age has been established long ago, as it has long been noted that the episodes of basaltic volcanism moved from one continent on to the other.

Each trap province has its own principal blanket of terrestrial traps, that is tufts and basalts derived from tholeiitic basic magma, saturated with silica, and younger local volcanic superstructures on this blanket, made up of specific lavas (alkaline-basic, etc.). The worn-down younger volcanic edifices have left behind only their stumps—dikes and plutons.

The time of formation of the principal blanket should be taken into account in considering the age of traps. Here, stratigraphy is the basis for age comparison; it indicates the occurrence of terrestrial traps in section—above and below the strata containing fossil organisms, traces of previous life. Absolute age determinations for igneous rocks also help to determine the age of traps. Such dating is especially important for intrusive bodies if they invade sediments but are not overlain by lavas. It is then clear that the enclosing rock is older than the intrusive one, but the age boundary of the igneous rock remains unclear. Finally, it is also essential for traps that the time of formation of volcanic edifices lying above the main blanket be known. A general notion of “superstructing basic rocks” can be put forward for all of them, with due account of the fact that various differentiates of the deep-seated basic (basaltic) and ultrabasic magmas are present among volcanic rocks.

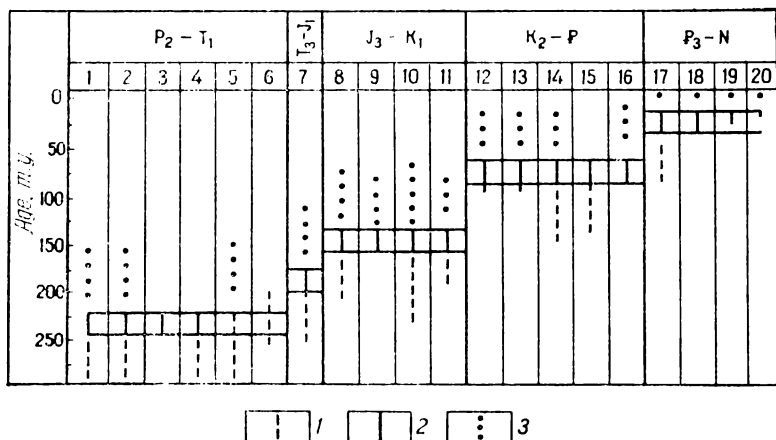


Fig. 8. Age of Mesozoic-Cenozoic extrusive and intrusive traps in different provinces.

Late Permian to Triassic epoch of magmatism: 1—Siberian craton—trans-Urals; 2—Taudeni syncline; 3—South Chinese platform; 4—Kashmir; 5—Appalachian Mts.; 6—Sverdrup basin. Late Triassic to Jurassic epoch of magmatism; 7—Karoo basin. Late Jurassic to Cretaceous epoch of magmatism; 8—Kaokoveld; 9—Rajmahal; 10—Parana and East Antarctica; 11—Australia. Late Cretaceous to Paleogene epoch of magmatism; 12—Deccan Plateau; 13—Brito-Arctic; 14—Greenland; 15—Spitzbergen (phase I); 16—East Verkhoyski Khrebet. Late Paleogene to Neogene epoch of magmatism; 17—Cordilleras; 18—West Antarctica; 19—Spitzbergen (phase II); 20—Iceland; 1—intrusive traps; 2—extrusive traps; 3—differentiated basic rocks overlying tholeiitic basalts

Trap seas of the same age are in the different areas of the Earth. But provinces formed consecutively, one after the other, frequently turn out to be close to each other. Let us consider how well the episodes of formation of volcanic seas of similar age correlate with each other and how many trap emplacement epochs had taken place as the Earth was being covered by its young outer basaltic shell (Fig. 8).

Late Permian to Triassic Magmatism. Very early in the Mesozoic, six trap provinces appeared on the Earth; they may in general be dated as Late Permian to Triassic. The province encompassing the Siberian craton and the trans-Urals is the best known of them. Here, a tuff unit accumulated late in the Permian, and the basalts of the principal trap blanket are dated as Early Triassic (radiometric age 235-220 million years) which is conformed to geological and stratigraphic observations.

The age of intrusive traps is more difficult to determine. Geological observations show that they are contemporane-

ous with lavas, but their radiometric age is frequently found to be greater (290-260 million years). As early as the 1950s, A. P. Lebedev and Yu. S. Krakovskii found these incompatibilities and suggested that the discrepancy between the geological (Triassic) and geochronological (Permian) dates was due to the enclosing sedimentary rocks affecting the intrusions being emplaced. Not only lavas are absent from the Permian strata but also appreciable tuffaceous beds.

The younger plutons (mostly dikes) of superstrutting basic rocks intrude the principal blanket; they are dated, on the average, at 210-218 million years (the turn of the Jurassic). The shield volcanoes that erupted trachybasalts and ultrabasic alkaline rocks belong to this period of intrusion. According to radiometric dates, however, these plutons were emplaced early in the Triassic (240-225 million years ago), that is they are found to be older than the basalts they intrude.

On the evidence of a rare network of boreholes, two intervals of trap magmatism are also distinguished in the trans-Urals and West Siberia: the first lasted from the end of the Permian to the beginning of the Triassic, and the second is marked by basalts with acidic rocks extending along Triassic to Early Jurassic grabens.

Information on the age of Siberian traps shows that the most vigorous episode of basaltic volcanism embraces an interval from 235 to 220 million years ago. Later, scarce eruptions along separate zones took place until early in the Jurassic. But with the many dates for the intrusions in mind, the interval of magmatism greatly expands downwards the time scale, which is difficult to correlate with the geological situation.

These inferences are important for analysis of the age of traps of other provinces on the Earth the information on which is less complete.

Late Triassic to Jurassic Magmatism. The Karroo basin is the only region in the world where the time interval of trap intrusion is known. The principal episode of lava eruption lasted about 15 million years, from the end of the Triassic to the beginning of the Jurassic. The prevailing radiometric dates are 170-190 million years. The superstrutting alkaline-basic rocks, shield volcanoes, and complex plutons are dated at 140-150 million years ago (the end of the Jurassic). Kimberlites were intruded precisely at that time.

Late Jurassic to Cretaceous Magmatism. The main episode of terrestrial volcanism lasted from after tuff emplacement late in the Jurassic to before the Albian (Early Cretaceous). The lavas are dated at 120-130 million years, and intrusions 120-150 million years ago. Differentiated basic rocks and kimberlites intruded 80 to 100 million years ago.

Late Cretaceous to Paleogene Magmatism. The dates for traps of Spitzbergen are most controversial; here, the lavas are eroded to a large extent and information was derived only from intrusive rocks. The main epochs of terrestrial volcanism were dated as the end of the Cretaceous—the Paleogene (45-62 million years ago). The intrusions were dated at 80-90 million years ago, some of them being considered as old as 140 million years ago. The superstructing differentiates continue to intrude through faults until Late Paleogene time (30 million years ago).

Late Paleogene to Neogene Magmatism. All early tuff ejections and subsequent lava outpourings began late in the Paleogene and continued until the Mid-Neogene, that is between 30 and 10 million years ago. On Iceland, the lava unit is exposed incompletely; that is why the oldest strata known here are only of Neogene age. In West Antarctica, the volcanites belonging to the so-called volcanic belt are composed only of basalts. The intrusions in the provinces of this age are dated only in the area of the Columbia Plateau of Cordilleras as Paleogene in age. Fault-derived, differentiated basic rocks are known in all provinces, their intrusion has been lasting from the end of the Neogene to the present.

Therefore, the onset of each geological period was marked in several regions of the Earth by violent magma extrusions. In practice simultaneously penetrating from deep in the Earth along a dense fracture pattern, lavas would spread over regions as large as half of the platform. Fissure extrusions would continue 10 to 12 million years. Earlier sporadic lava eruptions, intense explosive volcanism, and a forceful removal of volatiles into the atmosphere would take place each time at the end of the previous geological period with the resulting accumulation of tuffaceous sequences prior to lava outpourings. And this early episode would generally last 3 to 5 million years.

Trap seas appeared in impulses. Magmatic events were contemporaneous in widely spaced regions. The episodes of tholeiitic basalt outpourings ("common" traps) are most striking

ing in extent and shortest in time. All of them took place invariably at the turn of the relevant geological period.

All intrusive traps are radiometrically older. At the same time, the geological situation suggests that trap extrusions and intrusions are penecontemporaneous. Many dates for intrusions contradict geological and stratigraphic observations, for instance "older" plutons invade younger lavas.

Because of this discrepancy, in regions where lavas are strongly eroded the interval of magmatism expands, as it were, downwards.

After the Neogene, no regional tholeiitic basalt eruptions occurred on the continents. At present, the latest trap impulse is coming to an end. Only late magma batches are now intruding along faults in the interior of the youngest trap provinces.

In regions where extensive lava blankets have survived (Siberia, Deccan, etc.), obtaining old dates for plutons caused no problems. The geological situation was always here a limiting factor. It is from the analysis of the time of lava outpourings in such provinces that in 1969 the American geologist H. Kuno came to the conclusion that the plateau-basalt outpourings were geologically instant.

The age discrepancies are explained in two ways. Some believe that intrusions melt and assimilate the enclosing sedimentary rocks—Permian strata beneath Triassic lavas, Triassic strata below Jurassic lavas, etc. As a result, dates become older. An opinion is also expressed that extrusions make dates younger because of rapid cooling and because the magma loses some elements affecting age determinations. The former is more probable because the age of extrusions is usually conformed to stratigraphic data. Early magma intrusions also occur in each trap province, though their volume is small.

Along with the evidence for the older age of provinces, data are also available that each of the impulses is younger. These are dates for late superstructing volcanic complexes and plutons. Both also have tholeiitic varieties. They generally penetrate through the plateau-basalt blanket and the overlying sediment. The late igneous activity continues until the turn of the next geological period and coincides with the onset of a younger magmatic episode.

A new impulse may manifest itself both in the nearby regions and at any other point of the globe.

If we only take into account the time intervals of the main episodes of trap volcanism, namely basaltic outpourings of volcanic seas, all of them encompass only one fifth of the entire Mesozoic-Cenozoic. Each episode out of the five distinguished is discrete, that is no episodes of "intermediate" age are present. But if we consider all trap provinces in the context of a succession of formation episodes, together with late phases of activity in the trap provinces all over the world, we find out that in Mesozoic to Cenozoic time trap magmatism was almost continuous on the Earth. Of course, it manifested itself in each province as an episode limited in time.

The Age of Volcanic Seas on the Ocean Floor

Thus, peripheral (elevated on continents) parts of the outer basaltic shell of the globe appeared at once over great expanses as the result of separate episodes. Is it possible to distinguish basalt provinces having different ages within the basaltic blanket of the seabed? Is it possible that here, pouring out from a single parent fissure between the earlier adjacent continents (plate tectonics hypothesis), the basalts gradually changed in age, pushing apart older lava blankets together with the continents moving apart?

In order to find out whether or not the basaltic seabed includes vast areas formed geologically at an instant, that is like continental traps, one should take into account the age of rocks that lie on the lavas in the ocean (because the basalts have not been drilled through and for the present time it is impossible to date the first lava eruption) and the age of volcanoes that superstruct the basaltic blankets as either seamounts or large shield uplands. Let us recall that rocks derived from such volcanoes are always specific, differing from the tholeiitic basalts of the principal blankets. They are equivalents of the superstructing basic rocks of trap provinces. If a borehole in the ocean runs into igneous rocks of a volcano with specific rocks (alkaline-basic, etc.), the basaltic substratum of such a volcano—the principal lava blanket of the floor—is more ancient. On the continents, the time gap between the emplacement of the main tholeiitic lava sheet and accumulation of superstructing basic rocks usually equals 10-30 million years.

Considering the age of volcanic fields in the seabed on the

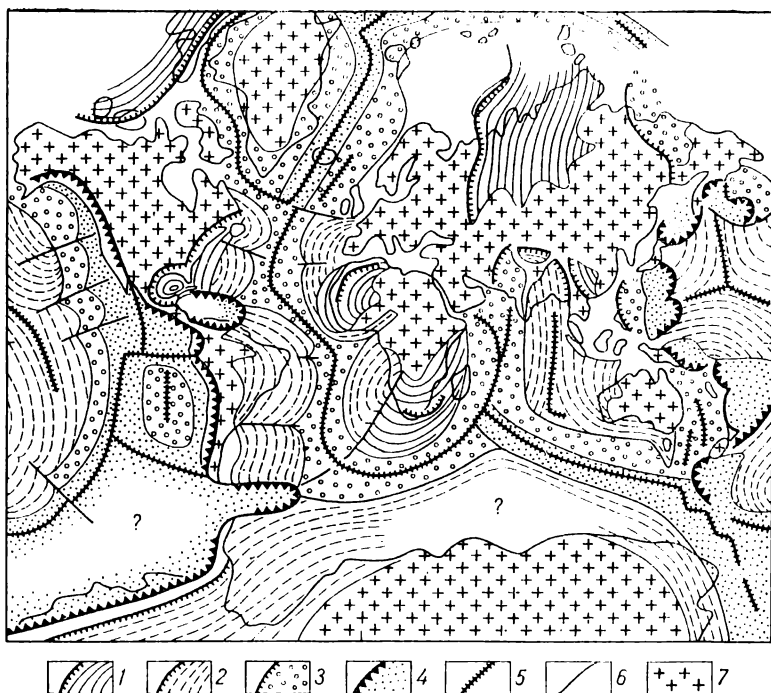


Fig. 9. Age of basalts in volcanic seas of the Earth's basaltic shell: 1 to 4—volcanic seas bounding continental and island mountains (1—Triassic seas near the Hercynides and Jurassic near the late Hercynides; 2—Cretaceous near the Cimmerides; 3—Paleogene near the early Alpides; 4—Neogene near the Laramides); 5—Oceanic ridges with rifts and volcanic mountains; 6—major fractures in the ocean floor; 7—continents not covered by basalts

basis of dredging and deep-sea drilling evidence, we note areas where the age of basalts in the ocean floor and that of basalts in the adjacent continental trap provinces are equal (Fig. 9).

The concept of pushing apart the continents (plate tectonics) implies a continuous sequence in plan of basalts of different ages from the margin of the oceans towards their centre. In the South Atlantic, however, Late Cretaceous basalts extend right to the Mid-Atlantic Ridge where they suddenly give way to Early Cretaceous-Paleogene basalts. (The same sharp change in the age of lavas has been established west and east of Madagascar.) In the Pacific, major

areas of basalts having different ages consecutively adjoin each other. Thus, Late Cretaceous basalts occur in the area of the Hawaiian Islands, Early Cretaceous-Paleogene basalts, east of them, and finally, Miocene basalts, along the coast (the last also occur on the continent). Therefore, it is more correct to speak of a discrete age succession of basalt areas, the boundary between them being somewhat blurred.

As in the trap fields of the continents, a pattern can be noted in the ocean according to which late superstrutting volcanoes tend to be restricted to fracture zones expressed of the surface as lineaments. Moreover, late magmatic outpourings continued to the onset of the next violent eruption episode. Therefore, if the basaltic fields that are consecutive in age neighbour each other, their boundary zones are the least distinct. Here, the data on the extrusive or intrusive occurrence of igneous rocks, as well as those on the relief of ocean floor bedrock, may help to distinguish areas where major episodes of tholeiitic basalt magmatism and late igneous activity have manifested themselves. After all, younger igneous rocks commonly make up topographic highs, specifically ridges. Of no less importance are the data on the composition of basic rocks. Tholeiitic varieties are generally typical of basaltic sheets, and alkaline-basic and other differentiates, for late volcanoes.

Indian Ocean. The basaltic floor in the eastern Indian Ocean existed as early as the mid-Early Cretaceous. The superstrutting volcanoes and blocks of the Ninety-east Ridge (with tholeiites) and chains of volcanic islands (with alkaline varieties) formed mainly at the turn of the Paleogene under the conditions of uplift. This basaltic field on the ocean floor approaches northwards (eastern Hindustan) and eastwards (western Australia) to the terrestrial trap fields formed as a result of the same two episodes.

The ocean floor along the southern and eastern coasts of Africa formed in the Jurassic, because as early as the first half of the Cretaceous it was overlain by thick clay and carbonate units. It is unknown whether a continuous basaltic blanket occurs here under the sedimentary layer. Most likely it exists in the bed of the Mozambique Strait towards which are inclined Triassic-Lower Jurassic lavas of the Karroo Province, South Africa. Dolerites of this age are also known on western Madagascar. A submarine ridge with grabens occurs at the centre of the Mozambique Strait. Here, the

superstructing alkaline-basic volcanoes had formed under-water rises by the beginning of the Cretaceous. The episode of magmatism along fractures was found to be the same both for the ocean floor and for the adjacent parts of the continent.

The lavas on the floor in the western Indian Ocean had been emplaced by the beginning of the Paleogene. Basalts and gabbros of this age were dredged from the rift valley. The superstructing igneous rocks related to the Mid-Indian Ridge and cross-cutting fractures (uplands) actively formed until Miocene time. The Deccan field with two episodes of magmatism—areal outpourings and alkaline manifestations along faults—converges with the oceanic lava fields off Hindustan.

Atlantic Ocean. The lava field emplaced in the western Indian Ocean in the Paleogene extends into the Atlantic, where it occurs centrally and stretches northwards up to the latitude of the British Isles. A number of boreholes ran here, at the centre of the Atlantic, into Eocene lavas and sediments. This implies that the lava cover itself accumulated as early as Paleogene time. That the lava floor existed here in Paleogene time is confirmed by the presence of large islands with volcanoes as high as 5-6 kilometres above the ocean floor. The summits of some islands exhibit young, Miocene volcanic rocks. Large massifs of volcanic islands rising above the older floor had been above sea level as early as the beginning of the Miocene and underwent wave action. These are Bouvet and Ascension islands, and the Azores. The episode of uplift and volcanism along fractures coincides with the formation of the horsts and grabens of the Mid-Atlantic Ridge. Then its troughs are filled with sediment, whereas volcanism is still going on on some islands.

The peripheral basaltic fields on the floor of the Southern and Central Atlantic were emplaced early in the Cretaceous, as follows from Cretaceous marine strata being widely developed above Layer 2 (lavas). The lava fields are complicated by volcanic superstructures along faults that extend into the continents. On the continents these faults are marked by alkaline-basic igneous bodies intruded at the end of the Cretaceous and in the Paleogene. As in the seabed, the igneous rocks restricted to faults of continents were emplaced after epochs of regional basaltic outpourings. Such outpourings took place in Parana basin, South America, and

in the regions of Namibia and Angola, Africa. These peripheral basalt strips in the ocean floor stretch northwards to the Bermudas, Grand Banks, and the Labrador Peninsula on the west and to the Bay of Biscay on the east.

In the broadest, middle part of the Atlantic, the marginal areas of the floor appeared much earlier. These are the Gulf of Mexico, and the floor off the United States and Senegal. In the Jurassic, probably already at the end of the Triassic, basalts were here covered by brine lagoons. On the western and eastern peripheries of the ocean, the continents subsided towards the Atlantic after graben systems with super-structing basic rocks had originated in the American Appalachians and on the margin of the Taudeni syncline in Africa.

The Paleogene median lava field of the Atlantic bifurcates north of Newfoundland; Paleogene basalts are here also developed in the ocean floor. Basalts of the same age are also known on the margins of the adjoining continents. The ocean floor is cut by fractures with related volcanoes made up of alkaline lavas, and dike swarms. The fractures extend into continental coasts. The volcanic rocks that occur along the fractures were emplaced at the turn of the Neogene.

The seabed along the northern Mid-Atlantic Ridge has been well studied in Iceland, where it is above sea level. The blanket is built up of Miocene lavas and is cut by a fracture system that is still younger. Volcanism along these fractures has developed since the end of the Neogene until now. Contrast basalt-liparite series predominate.

Arctic Ocean. Provinces in the floor of this ocean were distinguished tentatively because no drilling has been made here. The basaltic blanket in the middle of the Northern Atlantic can be extended along the median zone of the Arctic (along the Gakkel Ridge). Miocene basalts may lie in the principal blanket of the Arctic and Pliocene-Quaternary fracture-related volcanic rocks may occur along its rift valley.

The occurrence of Cretaceous dolerites in the north of Spitsbergen, on Franz Josef Land, and in Siberia east of the folds of Verkhoian'e makes it possible to suggest the occurrence of older lava blankets on the margins of the ocean (see Fig. 9). Cretaceous-Paleogene basalts were also found of Baffin Land, in the Davis Strait, and in the Labrador Sea. The basalt fields appear to be a continental extension of the lava province on the periphery of the Arctic

Pacific Ocean. In the eastern Pacific, a basaltic field similar in age and structure with the basaltic blanket in the middle of the Northern Atlantic extends along its submarine ridge. The volcanoes that straddle the fractures of the axial zone are Pliocene-Quaternary in age. This lava blanket continues into the continent, namely into the interior of the Columbia Plateau Province of the North American Cordilleras. The margins of the lava field around the strip of the East Pacific Rise have been formed earlier, by the beginning of the Paleogene, as confirmed by drilling. The fractures in this Paleogene blanket, as beneath the north-south Galapagos Ridge near South America, were straddled by volcanoes as early as the Neogene.

The central Pacific is structurally quite different. Its basaltic floor is the most ancient in the ocean. It had been generated by the beginning of the Cretaceous simultaneously over vast tracts. In the second half of the Cretaceous and in the Paleogene, volcanoes and islands grew over it.

The basalts on the floor in the western periphery of the Pacific form separate provinces of younger age. We shall dwell upon them later in the text. We emphasize here that the lavas are young throughout the western margin of the ocean. Some blankets had been emplaced by the beginning of the Paleogene; these are the West Philippine Sea, Coral Sea, and Tasman Sea. The youngest lava blankets had been generated by the beginning of the Neogene: the Shikoku basin, eastern Philippine Sea (Parece-Vella basin), Caroline basin, etc. All these western Pacific basaltic provinces of the ocean floor are not connected with the trap fields on the continents. No trap provinces are present on the continents adjacent to the western Pacific.

The provinces of different ages in the basaltic ocean floor, with fracture systems and volcanoes straddling them, are separated in Fig. 9 by straight boundaries, which is an obvious oversimplification. We do not know as yet the accurate delineations of each field. Almost each of the distinguished basaltic fields in the seabed extends into the continent, which helps to determine the time of lava accumulation on the floor since not only the end but also the beginning of epochs of regional volcanic outpourings on the continents are known.

An analysis of the age of lava fields in oceanic basaltic provinces though incomplete with today's knowledge, re-

veals belts or their separate segments of the following ages:

(a) Permian to Triassic, with a Triassic to Early Jurassic superstructure (north of the West Siberia, southeast of North America);

(b) Triassic to Jurassic, with a Late Jurassic to Early Cretaceous superstructure (southwest and southeast of Africa);

(c) Jurassic to Early Cretaceous, with a Cretaceous to Paleogene superstructure (margins of the southern and central Atlantic, along the periphery of the East Antarctica, south and west of Australia, and the Central Pacific);

(d) Late Cretaceous to Paleogene with a Paleogene to Neogene superstructure (margins of the northern Atlantic and Arctic, west of the Indian, west of the Pacific and its northern regions, and the central parts of the southern Atlantic);

(e) Paleogene to Neogene, with a Neogene to Holocene superstructure (the centre of the northern Atlantic, the centre of the Arctic, southeastern part of the Indian ocean, the most western Pacific and its eastern periphery).

Within all the fields distinguished, late igneous rocks of volcanoes and islands are related to oblique fractures. Along the belts composed in the ocean floor lava fields of different ages, zoning can be recognized along their trends. The age of fields changes along steeply oblique fractures. So each of the strips within the lava belt may be divided into segments.

It should be noted, also, that the mid-oceanic ridges include basaltic fields that are the youngest in the transverse zoning of the ocean but *not always the youngest* on the Earth. It is along the rift systems of mid-oceanic ridges that altered basalts enclosing ultrabasic bodies crop out. Ultrabasic rocks emerge along transverse fractures, especially in the walls of scarps, where they are enclosed in basalt piles.

Thus, the lavas on the floor of the modern World Ocean were emplaced as a result of the same five episodes of areal basaltic volcanism that were also established on the continents. Contemporaneous basaltic blankets of continents and oceans often pass one into the other. When each continental-oceanic basaltic megasheet had been formed, it was cut by a fracture pattern that passes from continent into ocean. At the same time central and shield volcanoes begin to rise along the fracture zones. They superstruct the principal basaltic blanket which could partly rise, with an erosion, within the continent, and partly submerge in the ocean.

Volcanic Seas of Continents and Geosynclines

Continental trap seas are located on plains, mainly on Precambrian cratons, though not on all of them. Thus, no Mesozoic-Cenozoic volcanic basaltic blankets have been established on the East European craton, nor on the vast North American craton, where trap provinces are known only on the margins of the Greenland block (see Fig. 9).

Even if cratons are involved in trap volcanism, called "magmatic activation" of cratons, the area of igneous activity does not cover the entire craton but selects, as though, a part of it. These are the western half on the Precambrian craton in Siberia, the eastern half of the craton of the same age in South America, and the most western part of the ancient craton in Australia.

In other cases, the same craton has undergone such activation several times. The African craton experienced this activation three times: at the turn of the Permian to Triassic in the northwest (Taudeni), at the turn of the Jurassic in the south (Karoo), and at the turn of the Cretaceous in the southwest (Kaoko Veld). So traps, even if they appeared mostly on Precambrian cratons, involved only some part of them, and "ignore" other parts or the entire craton.

It was noted, also, that if a trap blanket is located on the margin of a craton, it may well be next to a mountain region. Basic rocks also occur in this region, but mainly those called superstructing, that is younger than the principal blanket; they are commonly restricted to faults of the interior of grabens. Such cases were noted for the traps of Siberia and the trans-Ural, South China craton, and the adjoining mountains of Sikkim-Yunnan traps of Taudeni and the adjoining Atlas Mountains, and Karoo traps, where basic lavas and dolerite plutons are known on downthrown blocks (grabens) near the lava field in the southern mountains of the Cape fold system (see Fig. 9.).

As early as the 1930s, the famous geologist D.I. Mushketov gave attention to the fact that trap fields are located near mountains. Noting this for South Africa, he writes that mountain building and trap outpourings cannot be considered simultaneous phenomena. First fold mountains arise and then a vast basaltic blanket is emplaced. Later, in the 1950s, the same proximity of trap provinces to the neigh-

bouring mountains was noted by Yu.M. Sheinmann. He believed that the rise of mountains and lava outpourings might have been simultaneous. And these are interrelated phenomena. These constructions drew criticism, because there exist numerous mountain chains that surround cratons, and on nearby cratons foredeeps occur filled with molasses (clastic materials transported from mountains) but not trap blankets.

At the same time, there are regions where trap magmatism involved not a Precambrian craton but fold mountains. Basic rocks in grabens of the Appalachians and Ouachita (around the Gulf of Mexico) are the examples of it. The Columbia Plateau of traps in the Cordilleras is also located in the interior of young mountain ranges, being bounded by them on the west and east.

Traps have been found in the interior of fold structures fringing the Precambrian North American craton and on their outer side (on the backside of folds) along ocean coasts (on continental margins). Moreover, distinct foredeeps exist between fold structures and the craton. All this has prevented many geologists from agreeing with the suggestion that mountain building is directly associated with trap activity on the continents.

E. Suess called an area on the backside of folds "hinterland", having in mind a stable region on the internal side of an orogenic belt, or an internal platform. True enough, an ocean is located in the hinterland of the Appalachians; even younger mountains, on the backside of the Cordilleras, along the seashore; and also an ocean, farther to the west. The geological nature of the oceanic substratum on which basaltic blankets lie is still unknown. There are, however, regions on Earth where the hinterlands of continental mountain chains include traps. The best examples of them were found in the Urals and the trans-Ural (Fig. 10).

At the time of folding and mountain building, the Uralian strata, which accumulated in geosynclinal troughs, were displaced and thrust westwards, over the East European craton. A chain of basins filled with molasses, Cis-Ural region foredeep, formed in front of the mountains. East of the Urals, on the backside of fold structures, namely on the side from where the folded sequences were "splashed out" by a wave of crumpling, a trap sea was then formed. This was the area of traps of Siberia and the trans-Ural. Basalts overlay

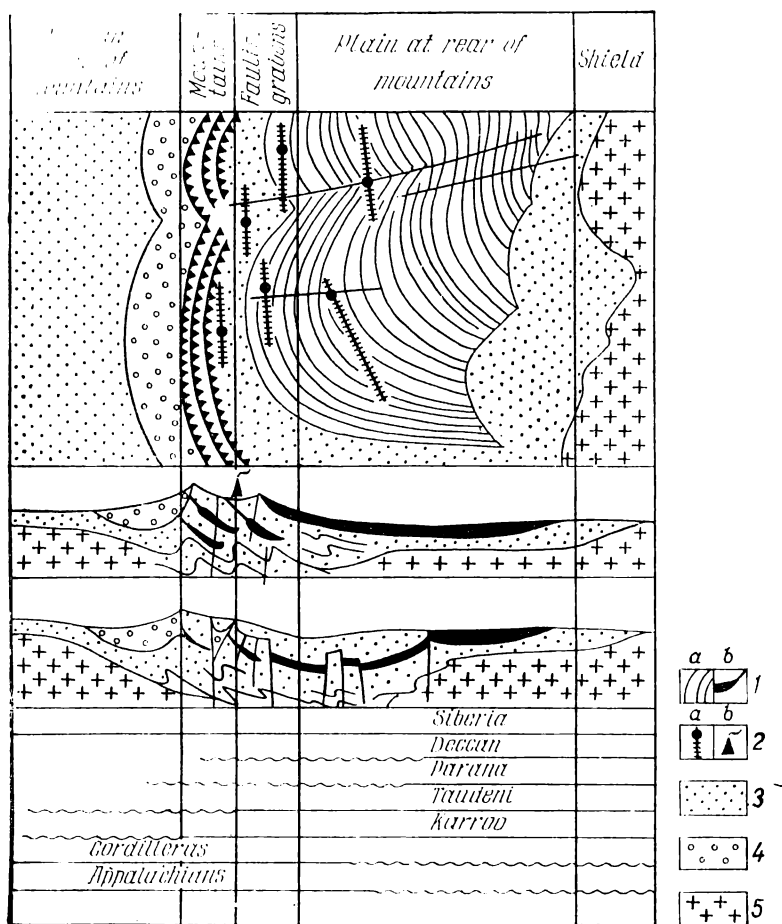


Fig. 10. Plan view and sections of the typical trap province of the Urals and Siberia as compared with other provinces.

The upper section shows the occurrence of traps immediately after their accumulation; the lower section, today's occurrence of the trap blanket under the sedimentary cover of the West Siberian platform. In the lower part of the figure straight lines denote trap distribution in other provinces and curving lines show areas now covered by ocean water: 1—traps (a—in plan; b—in section); 2—overlying basic rocks (a—in plan; b—in section); 3—sedimentary sequences; 4—sequences in the foredeep; 5—basement of the platform

folded sequences that accumulated at the time of downwarping of the geosyncline, and also series derived from local

mountain uplands, that is molasses of local intermontane basins. This implies that by the time of generation of the volcanic sea, mountains had risen and even been worn out.

Lavas issued onto the subdued surface of fold structures, and then the floor of the lava sea was again elevated and cut by faults into blocks, keys. The lavas were truncated by erosion on the elevated blocks, but they have survived in down-thrown grabens—depressions where the material transported from the elevated horsts was accumulated. The grabens were filled with erosion products at the time of continuing volcanism, which gave rise to basic rocks related to faults (contrast series of basalts and acidic liparites). These rocks correspond to volcanic edifices superstructing the principal basaltic trap blanket.

The most western grabens of the trans-Ural and West Siberia are located in the strip that is underlain by folded sequences made up of metamorphized igneous basalts and ultrabasic rocks of the early geosynclinal filling—the foundation of the Ural Mountains. Such geosynclinal basic and ultrabasic rocks are called ophiolites.

We reconstruct the situation in which the elevated fold mountains of the Urals were overlain from the east, within the hinterland, by a trap blanket of basalts. Recall that some of it accumulated slightly above sea level and the remainder, below sea level. At the time of formation of grabens still not intervened by eroded horsts, we could have seen a scenery resembling the flank of a mid-oceanic ridge. A basaltic blanket covers the westward rising flank cut by fractures. In the walls of fractures, young basalts are underlain by older, fragmented, crumpled, and metamorphized basic and ultrabasic rocks—ophiolites of the folded geosynclinal substratum.

Grabens that break the trap blanket lying on old fold mountains are called taphrogenic. The entire graben-horst system of an epigeosynclinal fold structure is called a taphrogen. The volcanic activity within the taphrogen broken into blocks, and divided into grabens and horsts, corresponds in structural location to igneous materials superstructing a basaltic trap blanket.

Of course, any mid-oceanic ridge has two flanks. While one of them can be compared with the situation in the trans-Ural in the epoch of trap magmatism, the other should be structurally similar to the ancient Urals and trans-Ural.

V.V. Belousov called the trans-Ural and West Siberia an unborn ocean. G. D. Azhgirei has shown that this depression resembles an ocean not only because it is located between two Precambrian cratons but also in the structure of the Earth's crust. When the drilling has shown that a basaltic trap layer, though discontinuous, occurs here at depths of 3 to 4 kilometres beneath young sedimentary sequences, its similarity to an ocean became even more complete. Basalts overlie here the basement of a Phanerozoic platform. The sedimentary sequence that overlies the basalts (it has accumulated on the taphrogen after its subsidence) is in a position in the Earth's crust as if it was a sedimentary layer on the ocean floor.

The trap blanket of the trans-Ural and West Siberia merges with the traps of the Siberian craton (Tungus syncline). Thus, the whole area east of the folds of the Urals was flooded by a volcanic sea of traps that overlay a platform-type region with the basement of varying age; it was a stable hinterland or backside platform relative to the Urals fold structures thrust westwards.

Thus, trap seas were formed only on the backside of fold mountains. Such regions were Siberia in relation to the Urals, the South China craton relative to the fold mountains of Sikkim-Yunnan, and the East Antarctic craton with reference to the fold structures of West Antarctica. The same platform-type hinterland frame was the northwestern part of Africa in relation to the Atlas Mountains and its southern part, to the Capides (see Figs. 9, 10).

Foredeeps were invariably generated, whereas basalts never issued, ahead of the frontal thrusts of all fold mountain chains on Earth. Such frontal frames were the East European craton ahead of the Urals and the folds of its southern mountain fringe, the North American craton ahead of the southeastern Appalachians and western Cordilleras, the Australian craton ahead of its eastern mountain chains, and the South American craton ahead of the Andes to the west (see Fig. 2).

There are also more complex cases, where both traps and a foredeep are present on the same craton and in the same zone of it (see Fig. 2). For instance, in the north of the Hindustan block, the traps of Kashmir occur in the same strip where the molasse of the Cis-Himalayan foredeep is developed. On careful examination, all such instances indicate

that a superimposition of features of different ages takes place. The craton first acted as a hinterland frame with reference to the adjoining fold mountains, then the situation changed and the craton was ahead of the front of younger folds in the next epoch of folding and thrusting. In this case, a foredeep was generated in front of a younger fold zone in a trap blanket emplaced on the backside of the older mountains.

To account for such instances, one should turn to geotectonic cycles, each of which was completed on Earth with the formation of fold countries. Knowing the geological age of episodes of basaltic magmatism that took place simultaneously on the continents and in the ocean floor, we can correlate these episodes with stages of various cycles.

According to observations, basaltic emplacement is actually related to mountain building not only in the context of *the place* of origin of volcanic seas (hinterland), but also of *the time* of rise of asymmetric fold mountains on Earth (Fig. 11).

Thus, all Permian to Triassic trap provinces occur near the Hercynides (Permian orogeny), all Triassic to Jurassic traps, near the late Hercynides (Triassic orogeny), the Jurassic to Cretaceous traps, near the Cimmerides (Jurassic orogeny); the Cretaceous to Paleogene traps, near the Late Cimmerides (Cretaceous orogeny), and the Paleogene to Neogene traps, near the Laramides (Paleogene orogeny). Therefore, each epigeosynclinal mountain building was accompanied by emplacement of a basaltic trap sea away from the direction of overfolding.

Figure 9 also shows other important features. Thus, the age of basalts in the Gulf of Mexico floor and along the coast off the Appalachians, close to continental Hercynian mountains thrust inward, is also Permian to Triassic. (We have already mentioned the terrestrial grabens in the hinterland.) The eastern margin of the Pacific lava blanket includes Paleogene-Neogene basalts off North and Central America, where the Cordilleras rise on the coasts, being overturned onto the continent during the Laramide orogeny. This implies that not only continental, trap seas, but also basaltic blankets in the margins of oceans are related in place and time to epigeosynclinal mountain building. The basaltic blankets in the ocean floor are situated in these regions as submerged trap provinces.

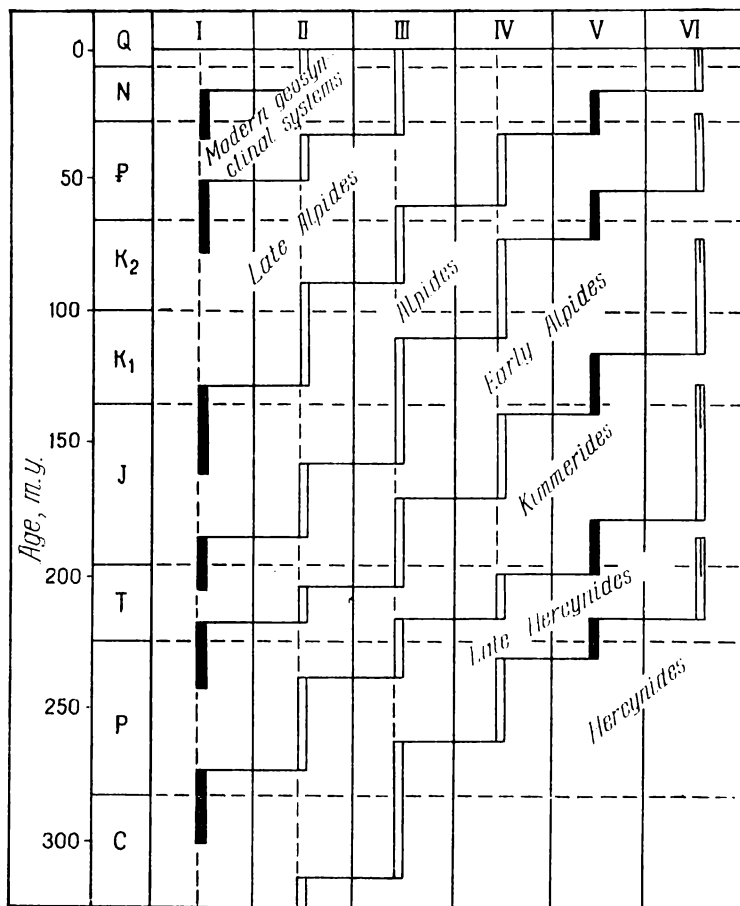


Fig. 11. Basalts in tectonic cycles:

I—initial basalts of geosynclines; *II*—sequences accumulated at the stage of geosynclinal downwarping; *III*—granitoids; *IV*—orogenic series; *V*—completing basalts of geosynclines, traps of platforms; *VI*—taphrogenic basic rocks, alkaline basic rocks of platforms

It is also seen in Figs. 2 and 9 that in some regions continental traps are separated from the fold zones of "their own" orogenic epoch by younger fold orogenic zones. This is most characteristic of the periphery of Hindustan. A narrow strip of younger, late Alpine fold structures extend along the west-

ern, northern, and eastern peripheries of the Hindustan platform, separating three trap regions of different ages from the fold regions responsible for their generation. These fold regions (Belujistan, the Himalayas, Arakan-Yoma) are now at the epigeosynclinal orogenesis stage.

The geosynclines that gave rise to these mountains and received sediments in this strip were initiated as troughs in basalts that are extensions of lavas of trap provinces. When other geosynclinal columns had been accumulated above the basalts, the folding took place and mountains rose and were thrust on three sides towards Hindustan. Foredeeps that are still receiving sediment invariably occur now in front of the structures. The basaltic lavas that lay on the bottom of the troughs were folded and occur now inside the thrust structures as ophiolites.

This implies that the emplacement of a trap blanket coincides not only with the close of folding and completion of an orogenesis. The blanket itself may serve as a basaltic bed in which a geosynclinal trough, that is a "cradle" of would-be fold mountains, is initiated. It follows then that basalt outpourings not only crown a geosynclinal, or geotectonic, cycle, but also "open up" a new cycle (see Fig. 11).

Along with the confirmed views by D.I. Mushketov that trap outpourings take place when fold mountains are worn down, other scientists observed that traps corresponded to an epoch of early basalt accumulation in a geosyncline from which fold mountains then rise. This correspondence has been substantiated in the greatest detail by the petrologist D.S. Shteinberg. His views were shared by other petrologists, M.B. Borodaevskaya, A.A. Marakushev, and O.A. Bogatkov. In the North American Cordilleras, the Columbia Plateau traps were emplaced in the west, on the backside of the Laramian fold structures in front of which foredeeps were initiated east of the mountains; these traps completed the orogenesis of the Laramian tectonic cycle. At the same time, the westernmost part of the basaltic lava blanket was accumulated at the time of more rapid subsidence, and the basalts are immediately overlain by sediments of volcanic islands, namely rhythms of clastic sequences characteristic of geosynclinal deposition. Then, as late as the end of the Neogene, fold mountains of the Coastal Ranges (on the continent) rose from this (Pacific) geosyncline. In their interior, the basalts, which have the same age and

similar in all aspects with gently inclined traps of the Columbia Plateau, are folded and metamorphosed early geosynclinal materials, that is ophiolites of the present-day epigeosynclinal mountains.

In this region as on the periphery of Hindustan, the episode of basaltic magmatism on the backside of fold mountains that rose from the now disappeared geosyncline, was at the same time an episode of magmatism in a newly initiated geosyncline. A geosynclinal trough may not originate in the hinterland. Then the traps survive as a gently lying blanket. Only part of such an undisturbed blanket may be preserved, whereas the other may occur in the interior of a young fold region. Such a situation is just the case for the Cordilleras (North America).

The concept of initiation of new geosynclinal troughs on the backside of the formed fold zones is classical in geology. This pattern was emphasized by the renowned geologists L. Kober and R. Staub, as well as by Acad. N. M. Strakhov. Acad. V. I. Smirnov develops the view that young geosynclines retreat away from the more ancient ones. This process was differently explained by scientists, and some assumed that partings of the Earth's crust were active behind overfolding against the stable front. The direct link between thrusting of mountains forward and parting processes on the backside of fold zones is, however, ruled out by a considerable time gap of 30-40 million years existing between the two endogenic episodes, folding and hinterland basalt emplacement (see Fig. 14). The basaltic outpourings at the end of a geotectonic cycle of folding and mountain building were called final magmatism by the German geologist H. Stille, because he believed that after these emplacements the region becomes very rigid and no new troughs can be initiated here. At the same time, concerning some regions of the Earth, H. Stille showed that some of the regions, in which the final basalts had issued, were later transformed into geosynclinal regions (southeast Asia and Indonesia). Therefore, the final lavas of one geotectonic cycle are at the same time the initial basalts of another.

Besides basalt blankets that are located on the continents on the backside of fold mountains, continental margins also include trap provinces that are bounded by the ocean floor but not by mountain chains (see Fig. 9). In all such cases the basalts of the ocean floor are of the same age as the near-

by continental trap blankets. All such provinces (Parana, western Australia, that of Kaoko Veld, the eastern and western parts of Greenland and smaller areas in the eastern part of Brito-Arctic province) include localities of continental trap blankets superposed on Precambrian cratons

Each Precambrian craton is bounded on the continent by cratons whose basement is younger. Sedimentary "stages" may be distinguished in the cover of any Precambrian platform, which reflect the evolution of this platform at each epoch of a geotectonic cycle. Thus, if a geosyncline neighbours a Precambrian platform at any geotectonic stage, all the strata of the sedimentary cover become thicker towards it.

Major episodes of subsidence and mountain rise in the neighbouring geosyncline are reflected in the sedimentary cover of the platform. Thus, deep-sea clays of geosynclines invariably correspond to the platform of marine clay or carbonate strata. Platform equivalents of orogenic molasses in the adjoining fold mountains are always coarse-clastic continental units, commonly coal- or salt-bearing, depending on the climate of that epoch. On frontal platforms, these units, contemporaneous with the mountain building period (synorogenic), are usually confined to a narrow foredeep. On hinterland platforms (beneath traps), synorogenic continental formations are developed widely.

Each trap field in an oceanic margin is underlain by a certain set of sedimentary sequences. These are invariably becoming thicker towards today's oceans, which may reflect strata thickening towards geosynclines earlier present in oceanic areas. Coarse-clastic strata below traps always indicate that the source area was in a region now occupied by the ocean; therefore, it must be assumed that this region had been previously occupied by mountains that were worn down and brought these fragments. Finally, the sets of sedimentary units grading from marine at the base to continental synorogenic at the top of the section (immediately below traps) are quite similar in type and age to the units that underlie the traps of the same age near the real continental fold mountains.

This suggests that oceanic basalts, which are extensions of the continental trap blankets of the same age, may be underlain by fold zones that had earlier existed as epigeosynclinal mountains under the basalt floor. By the age of the lavas of

traps and of the seabed, and by the set of sedimentary units that underlie traps and have survived on the continents, we can judge what precisely fold zone must be subsided near the edge of the continent.

The proponents of plate tectonics and continental drift group the different continents together in order to restore their total structure as if it preceded the situation when they were pushed apart. The grouping of continents is a result, that traps emplaced in different geotectonic epochs and thus of different ages are at an artificial contact. Moreover, none of the trap blankets of different ages turns out to be next to a fold zone, as is the case in wholly continental areas. Sedimentary strata that underlie traps also join each other by their thick zones without mutual correspondence. Members and units of similar composition prove to differ in age. This is especially well seen if the eastern coast of South America is attached to the southwestern coast of Africa.

Explaining their method, the proponents of plate tectonics refer to a torn-off newspaper sheet two parts of which have "spread" as two continents and thus opened up an ocean-floor. Having matched the torn-off edges, one is supposed to read the previous geological history of an earlier single continent. But having combined the continents of South America and Africa in this way, the "newspaper reader" finds that the matched shreds of the newspaper are from different dates.

It is South Africa, to which the edges of other southern continents are usually matched thus "restoring" the once single megacontinent of Gondwana, that has a unique vertical set of sedimentary units overlain by traps. This set corresponds to the development of the region at a Late Hercynian geotectonic cycle. The traps of other southern continents (Antarctica, South America, Australia, and Hindustan), together with the underlying sets of sedimentary units, were formed in other (various) geotectonic cycles. The upward change from marine to clastic continental sediments beneath traps takes place everywhere in one manner and in one direction but at different times.

To explain the formation of these single-type rock complexes on each of the continents, it is necessary to assume a previous existence of "lacking" structural zones near their coasts. These could have been only geosynclines with their early downwarping and subsequent mountain building. Erosion

of mountains led to the accumulation of synorogenic units distributed over extensive sedimentary basins of hinterland platforms the parts of which have survived on the continents. The basins were then covered by trap blankets of different ages. The Jurassic-Early Cretaceous traps completed the Cimmerian geotectonic cycle (South America, Australia, East Antarctica); the Triassic-Jurassic traps were emplaced at the end of the Late Hercynian cycle (South Africa); and the Cretaceous-Paleogene traps closed the early Alpine cycle of tectogenesis (West Hindustan).

Volcanic Seas on the Ocean Floors and Island Arcs

If we trace the age of oceanic lavas near mountainous coasts, where folds were pushed over continental platforms, we find out that the age and location of volcanic blankets on the ocean floor are the same as those of continental trap provinces.

The western Pacific is a region where such constructions can be checked by using the above parameters. In this part of the Pacific arcuate chains of islands and seamounts stretch along mountainous coasts typical of the Pacific margins. Islands are made up of fold geosynclinal units, the same as those known on the continents. Seamount arcs usually consist of volcanoes superstructing blankets of the basaltic floor of different ages (Fig. 12). Because fold structures occur on the islands of different ages, it should be found out whether or not the ocean floor lavas on the backside of these structures correspond in age to the completing basaltic blankets.

The western Pacific is also regarded as a belt of present-day geosynclinal systems, because it is here that the deepest troughs and chains of volcanic islands exist on Earth. This permits checking the other of the above postulations, namely that geosynclinal troughs are usually initiated in the completing basaltic blankets on the backside of fold mountains.

A pattern has long been established on the Earth that fold regions of varying age are usually composed of a certain complex of single-type formations but of different ages (see Fig. 11). Geosynclinal basic rocks (ophiolites) occur at

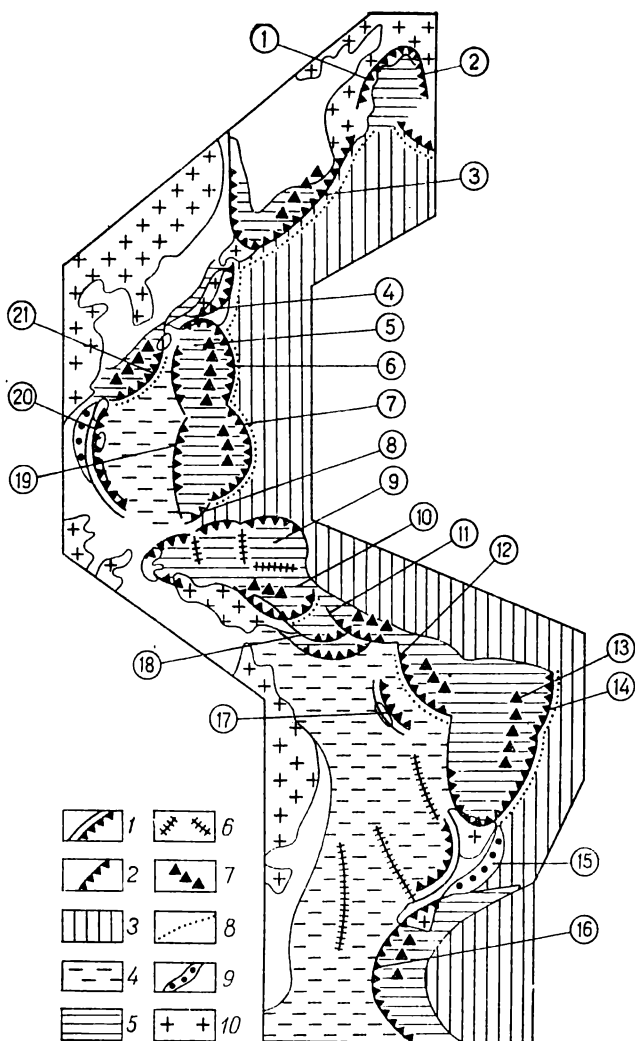


Fig. 12. Volcanic seas and island arcs in the western Pacific:

1—Olyutorski Range; 2—Shirshov Range; 3—Kuril arc; 4—Fossa-Magna zone; 5—Shikoku basin; 6—Bonin arc; 7—Mariana arc; 8—Yap arc; 9—Caroline basin; 10—Bismarck Sea; 11—Solomon arc; 12—New Hebrides arc; 13—Colville-Lau Ridge; 14—Tonga-Kermadec Ridge; 15—Hikurangi trough; 16—Macquarie Ridge; 17—New Caledonia Island; 18—Woodlark arc; 19—Parece-Vella Ridge; 20—Philippines; 21—Ryukyu arc.

1, 2—fold island arcs (1—early Alpine, again folded in the Neogene; 2—Laramide); 3 to 5—basaltic blankets of different ages (3—Cretaceous; 4—Paleogene; 5—Neogene); 6—submarine ridges of joined arcs; 7—chains of volcanoes on Neogene basalts in modern geosynclinal systems; 8—deep-sea trenches in front of modern geosynclines; 9—foredeeps—sediment-filled trenches in front of the Neogene fold mountains; 10—continents and large islands

the base of the complex, above lie terrigenous units (flysch) and intermediate volcanic rocks, and still higher in the section, coarse-clastic orogenic molasses in the interior of intermontane basins, together with which intermediate, more seldom acidic volcanic rocks, lie.

All of the Earth's fold geosynclinal zones that rose as mountains in the Paleogene (Laramian geotectonic cycle) contain fold ophiolites of Late Jurassic to Early Cretaceous age, terrigenous-volcanic flysch of Late Cretaceous age, and orogenic molasses of Paleogene age. The older, early Alpine fold zones contain Triassic-Jurassic ophiolites, Late Jurassic flysch, Cretaceous orogenic sequences, etc. (see Fig. 11).

Of course, fold regions may also include more ancient sequences, because a geosyncline of any cycle is invariably initiated in a substratum in which some blocks are older.

Having found in the island chains at least some of the characteristic units of a certain age, one may assign the fold mountain arcs to a definite geotectonic cycle.

The Macquarie Ridge is the southernmost island arc of the fold Laramides. At the base of the arc Jurassic-Cretaceous basic rocks of the ocean floor were deformed late in the Cretaceous, metamorphized, and thrust westwards. Completing basalts of Miocene age occur in the back-arc zone. A trench (foredeep) in front of the arcuate ridge occurs in the Paleocene basaltic bed of Tasman basin. Andesitic volcanoes of back-arc island rises lie on young basaltic floor.

In **New Zealand**, two fold arcs are conjugated by their fronts. They contact each other and are displaced along a fracture. The northern one is convex eastwards, the southern, westwards, and the folds are thrust in the same direction. Folding took place at the turn of the Cretaceous (Rangitata orogeny), and then geosynclines of the next cycle developed in the back-arc zone in completing basalts of Cretaceous to Paleogene age. Their strata were folded and thrust in the same direction at the turn of the Neogene (Kaikoura orogeny). The trench, which stretches along the front of the northern fold arc, is a foredeep.

Tonga-Kermadec and Colville-Lau Ridges, mutually parallel and slightly convex eastwards, are intervened by the broad Havre-Lau depression in the basaltic substratum of Miocene age. The presence of Paleocene orogenic series in the Tonga Ridge (Eua Island) points to the Laramian oroge-

ny responsible for the base of the ridge, in which Early Cretaceous ophiolites are present. They were dredged from the island side of the Tonga Trench. Probably, the belt of Laramian folds runs from the Kermadec Ridge along northern New Zealand and then bounds on the west (Three Kings Ridge) South Fiji basin with young, Miocene lavas lying on the floor. These basalts are the closing lava outpourings on the backside of the Laramian orogenic oval.

The New Hebrides arc, convex southwestwards, is composed of several island chains. The frontal chain includes orogenic units of Paleogene age on the Laramian basement. On the central and the eastern islands Miocene basalts are known in the back-arc zone. Deformation is under way in the young lava blanket zone, and eruptions are observed in the central island chain.

The Loyalty Islands have a volcanic base built up of Miocene seamounts. These superstruct the more ancient, Paleogene basaltic floor and occur on the backside of southwest-thrust structures of **New Caledonia Island**. Early Alpine orogeny is manifested on this island. Completing Paleocene basalts are developed on the backside of these structures.

The double arc of the Solomon Islands has resulted from crumpling and slight southward thrusting of Lower Cretaceous basalt slabs. Deformation took place at the time of the Laramian orogeny. Folding and metamorphism are better documented in the northern island chain, but are also known at the base of the southern chain. Orogenic coarse-clastic units and intermediate volcanites are of Paleogene age. Miocene lavas, closing for the Laramides, lie on the backside of the structures and in an inter-arc depression. The southern chain of volcanic islands is a volcanic cordillera lying on young lavas. A trench stretches in front of the arc, as does a seismofocal zone dipping beneath the arc.

The Woodlark Rise bounds the Solomon Sea on the south. On the Papua Peninsula, New Guinea, which is its extension, there is clearly manifested the Laramian orogeny, with folding and southward thrusting of Lower Cretaceous basic rocks. Another arcuate segment of the folded Laramides stretches from Papua as the Pocklington Rise and separates on the south Moroi Basin. The hinterland, inner-arc ovals of the Solomon and Moroi Seas subsided in the Miocene following the appearance of basaltic tuffs, an indication of closing magmatism.

The **Bismarck Sea** is surrounded by the Laramides. The basin on the backside of the Bismarck Sea subsided in the Miocene. The process was accompanied by basalt magmatism.

The **New-Ireland-Manus island arc** bounds on the north the Bismarck Sea. The base of the islands consists of the Laramides. An epoch of Miocene subsidences (closing for the Laramides) has been established on the islands.

Structurally complicated **Caroline basin**, with internal ridges, is located north of the Bismarck Sea. The basin can be combined with the western oval of a small fold Laramian arc of Halmera Island. The basalts lying on the floor at this locality are of Miocene age, an indirect indication that fold structures of the Laramian consolidation phase occur in the interior of the rises and on the margins of Caroline basin.

The **Yap, Mariana, and Bonin arcs**, convex eastward, are of the same type. Each of them has an outer mountain arc built up of basic rocks that were thrust eastwards at the time of the Laramian cycle. The fold complexes are overlain by orogenic units of Paleogene age. The hinterlands of the arcs (Parece-Vella Basin and Shikoku Basin to the north) have their floor covered by Miocene lavas that are closing for the Laramides. The volcanic arcs, which lie here on young basalts, and inter-arc troughs are cordilleras and troughs of a modern geosyncline. Trenches extend in front of the eastern arcs, being foredeeps in the ancient ocean floor with Lower Cretaceous basalts.

The **Kyushū-Palau Ridge**, at the centre of the Philippine Sea, is composed of volcanic islands. Paleogene orogenic units with fragments of Cretaceous rocks are exposed on its flanks. Block structure, with westward thrusts, is characteristic of this submarine ridge. Thus, the Miocene basaltic blanket of a basin east of the Parece-Vella Ridge lies inside two oppositely convex Laramian fold arcs. Their fold complexes are thrust outwards. The northward continuation of the Kyushū-Palau arc is the Daito Rise, which bounds on the west Shikoku basin with Miocene lavas.

The **West Philippine Sea**, with the Paleogene basaltic floor, neighbours the **Philippine Archipelago**. The features of the early Alpine fold structures occur here. The Paleogene basaltic blanket is the closing one.

The Bonin volcanic chain come near to the **Japanese island arc** from the south, especially the Fossa Magna zone. On the islands of the eastern Bonin arc, Laramian orogenic

sequences of Paleogene age are known. Miocene lavas lie in the back-arc Shikoku. This basin is bounded on the north-west by the structures of Japan. Its base consists of fold rocks of many orogenies each of which manifested itself in zones that migrated southwards. Geosynclinal troughs were initiated in the lavas closing for the tectonic cycle.

Some regions of Southwest Japan, near the Fossa Magna zone (Tanzawa Island) and in the far south of Kyushū Island were subsided and covered by basalts in the Miocene. The subsidence was there at the time of Laramian final manifestations near localities where folding with northward thrusting is known. The Laramian structures are a continuation of the Bonin cordillera along an arc that is convex westward, and close the Laramian fold oval of Shikoku Basin in the north. In its interior, Miocene basalts are general.

In North Japan, a Laramian fold system, convex eastwards, is developed on Honshu and Hokkaido islands, north of the Fossa Magna zone. A modern chain of volcanoes exists in the hinterland on a Miocene basaltic blanket which is closing for the Laramian orogeny (green tuff suite). The basalts extend into the floor of the Japan Sea. They are considered to be geosynclinal in the west of Kyushū Island.

The occurrence of the completing post-Laramian basalt blanket of Miocene age in the Japan Sea shows that Central Japan coincides with the junction of the fronts of two Laramian arcuate fold belts. One of them is south of the other and bends away from the Bonin arc near the Fossa Magna zone; the other is part of the Northeast Japan arc and is convex away from the Japan Sea. The northern and southern coasts of Japan are regarded as zone of a present-day geosyncline in a young Miocene basaltic blanket.

The Ryukyu arc joins the belt of Japan at an angle and is an extension, as an island chain convex southward, of the zone of modern volcanism. The Laramian base, back-arc Miocene basalts, and a trench—a foredeep in front of the arc—all these are characteristic indications of today's geosynclinal system. A deep-seated seismofocal zone dips beneath these structures.

Two branches of the Laramian fold systems deviate from the centre of **Hokkaido Island** (northern Japan) towards Sakhalin and Kamchatka. The western branch is thrust westward. Laramian folds are also known on the islands of the Minor Kuril Ridge. Closing basalts of Miocene age are known

at the southern closure of this fold semioval, inside the concave belt in the north of Hokkaido. They also appear to lie in the floor of the South Kuril deep-sea back-arc basin. Miocene basalts are also known at the backside of the fold complexes of Sakhalin. Tatar Strait basin is in front of the Sakhalin Mountains and resembles a foredeep.

The Minor Kuril chain extends into the uplifts on the eastern peninsular of **Kamchatka**. The interior volcanic chain of the Greater Kuril volcanoes, which is underlain by Miocene basalts, is also traceable northwards over the young volcanic belt of Kamchatka. The Laramian fold structures of North Kamchatka fringe the northern part of this peninsula as an arc and extend into the Shirshov range. The basaltic floor of the Kamandor Basin, with the closing Laramian lavas of Miocene age, is located inside the concave arc. The Olyntor region of today's folding, with westward thrusts is now developing on the interior side of the Laramides of Kamchatka.

The evidence on the West Pacific margin shows that arcuate or oval fold zones of different ages can be distinguished in this region. Stable masses covered by closing basalts occur in their interior. In each segment and even in any section, the fold zones exhibit interior and frontal areas. That the arcs and ovals are simple in plan in each cycle of folding allows one to predict the extension of these structures.

Basaltic seas are invariably located on the backside of outward thrust fold island systems that are arcuate or oval in shape. All present-day volcanic submarine and above-water mountains superstruct young, Miocene lava blankets. Troughs that were also initiated in the floor with young basalts occur between chains of volcanic islands and frontal fold arcs. It is these zones that can only be treated as modern geosynclines behind mature systems.

Deep-sea trenches in the older basaltic seabed occur in front of convex fold arcs. The basalts are of Early Cretaceous age. All the geosynclines of the Earth, initiated in the basalts of this age, were folded in the Laramian epoch (see Fig. 11). Frontal deep-sea trenches are structures of the type of foredeeps in the stable block at the centre of the Pacific.

Thus, the principle of establishing the backside and the frontside of a fold system can be applied to tracts of the ba-

saltic ocean bed. Here, we can also show the constant place of generation of rounded volcanic seas in the interior of fold mountain arcs and ovals.

It is important to note that in island fold structures the basalts of the same age with old lavas in the ocean floor are deformed and displaced outward, toward the convexity of the arcs. This implies that before a young basaltic sea is emplaced the ocean floor with old basalts is deformed along arcuate or oval-shaped concentric zones. Downwarping (first develops geosynclinal deformation) and then uplift (orogenic deformation). Deformation takes place in such a way that the sedimentary sequences of active arcs and concentric zones migrate outwardly. An impulse of active movements directed radially from the Earth's interior creates near the surface a tangential, centrifugal "geosynclinal wave".

Basaltic blankets in the ocean floor can be described in terms applied to continental trap seas. Therefore, we shall try to apprehend from the same standpoint the structural implication of major linear basaltic blankets of different ages in the interior of the oceans. The age of basalts is an indicator of a certain fold zone of one or another tectonic cycle (Fig. 11). Such a zone may have existed in regions covered by the ocean before the emplacement of each completing lava blanket.

Figure 9 is a scheme of the patchy and banded Earth's shell made up of basalts of different ages. The basaltic bands and patches are becoming younger outward from each Precambrian continental craton. A similar role of a stable block (for the Mesozoic-Cenozoic) is played by the central Pacific.

Are Continental Basalts Similar to Oceanic Basalts on Earth?

Prior to active dredging and drilling in the ocean, it was considered that all oceanic basalts are the same as on islands, that is differ in composition from "common" traps -tholeiitic basalts—mainly by the greater amount of alkalis and lesser amount of silica. Dredging and drilling have shown, however, that bedrock basalts of the ocean floor are the same tholeiitic lavas rather rich in silica. At the same time, detailed studies of their chemical compositions have

revealed that distinctions do exist and are persistent. They mainly lie in that the potassium content of ocean floor tholeiites is on the whole lower (0.3% K_2O and less), unlike the average for traps (0.6-1%). Other distinctions are less striking.

However, the more information was obtained about bed-rock floor lavas, the more frequently rocks of somewhat different compositions were found. Thus, in the rift zone of the Mid-Atlantic Ridge (43°N), lower-silica tholeiitic lavas, resembling those making up islands (they are called tholeiitic basalts of islands) emerge at the very bottom of the cleft beneath typically oceanic lavas. Moreover, alkaline basalts that are similar to those building up the summits of islands have been studied in the lower strata of the lava sequence.

A pattern has been revealed, according to which, as in trap provinces of continents, alkaline basalts or basaltic varieties similar to ultrabasic rocks occur both in the lower strata of the lava sequence and in the upper strata, where they superstruct a tholeiitic basalt blanket as major shield volcanoes.

It has also been found that low-potassium oceanic basalts also contain members with lavas quite similar to trap tholeiites.

Obviously, if we deal with the average composition of tholeiitic basalts of traps, we may come to somewhat wrong conclusions. It has earlier been said that trap sequences consist of lavas of different compositions. The author has analyzed changes in the chemical composition of rocks from the lower to upper strata of the lava blanket by using the information provided by many students of the different trap provinces of the Earth. It has been revealed that varieties with the highest alkali, including potassium, contents occur at the base of tholeiitic lava blankets; here also commonly lie alkaline-basic trachybasalt lava sheets proper. At the same time, the uppermost tholeiitic basalt units contain the least amount of potassium (0.4-0.2%, unlike common 0.6-0.8%), and these units at the top of continental lava blankets are indistinguishable in composition from "oceanic" tholeiites.

It should be noted that such lava sequences at the top of trap blankets are as thick as hundreds of metres but are not omnipresent. This is because the top of a continental trap blanket is eroded most easily. Therefore, major out-

crops of upper lava sequences have survived only in the interior of depressions. But even if the upper lavas have been washed away, their roots—vents of dikes and intrusive bodies—are preserved. Thus, in the Tungus syncline, thick low-potassium tholeiites (lower Kogotok Formation) have survived only in the northeast, but dikes of traps of such a composition occur extensively in the north. In the Columbia Plateau trap field, the upper, lowest-potassium lavas of the Pomona Beds make up only remnants, but dikes, their vents, are developed widely. On the Deccan Plateau of Hindustan, the youngest dikes, vents of now eroded lavas, best resemble oceanic lavas in composition. By the end of accumulation of the principal trap blankets, when the Earth's interior and crust are most heated because of prolonged volcanism, lavas contain the least amount of potassium and are the most similar to the lavas at the top of oceanic blankets.

No complete information on the chemistry of oceanic basalts has yet been collected, since boreholes penetrated only tops of the lava sequence in the floor, that is sheets that correspond to the topmost traps of continental blankets. The oceanic lava blankets have subsided; therefore, their upper strata have survived completely. In the rifts of mid-oceanic ridges, these strata emerge only at the base of scarps, and secondary alteration due to displacement along fractures are frequently found in them. On the basis of extensive evidence on basaltic rocks from all the rift zones of mid-oceanic ridges, N.A. Kurentsova has demonstrated in a conclusive manner that such low-potassium basaltic units of the principal blankets of the floor are invariably superstructured in rift systems by still younger members of tholeiitic basalts (properly rift basalts). She describes the basalts of the principal ocean floor sheets as ferruginous, lying at the base of oceanic fractures, and the upper rift lavas proper as magnesian. Such rocks are unknown outside rifts, and there they make up cones and their substratum.

If the rift valley of a mid-oceanic ridge is shallow, ferruginous basalts are not exposed at all. In such cases, lavas in the walls of the rift valley consist only of magnesian, low-potassium rocks, and these are always younger than the principal blanket in the ocean floor (Fracture of 37°N in the Atlantic, the rift of the Mid-Indian Ridge, and many others). Along with these magnesian tholeiites (properly rift basalts), the crust is invaded by intrusive bodies that

are distinctly layered and they are much alike plutons of trap provinces (in Siberia, they are plutons typically occurring at Norilsk). These bodies are composed in their lower parts of ultrabasic rocks with plagioclase (lherzolite, troctolite). Rocks containing more silica and alkali lie high in the pluton. A.A. Marakushev believes that the magma may become layered owing to liquation.

Magma stratification in shallow chambers and further eruptions are responsible for an alternation of outpourings of contrast compositions ranging from ultrabasic lavas (pycrites) to those rich in alkali and silica.

Ferruginous tholeiitic basalts of the top of the seabed emerge in rift valleys that expose the ocean floor to a great depth. Here also occur ultrabasic rocks. Geosynclinal ultrabasic rocks of continents—plagioclase-free alpinotype ultrabasic rocks (dunites, harzburgites) are equivalents of these ultrabasic rocks in chemical composition and degree of transformation (serpentinization, that is water addition). In geosynclines of continents and in oceanic rifts, such ultrabasic rocks are not genetically related to ferruginous tholeiites, but are spatially associated.

The materials, summarized by N. A. Kurentsova, prove once more that the floor of the rift valleys in the oceans displays an igneous rock complex that both resembles traps and geosynclinal, folded and severely altered rocks. The rocks similar to geosynclinal rocks lie at the very base and higher the rocks similar to traps. The youngest rift complex (properly rift complex) of magnesian lavas and layered plutons is only similar to young rocks occurring in the grabens of stable trap regions. Here, magma may slowly cool to become stratified before it will be transported to the surface as individual batches of the already separated melt.

* * *

Let us emphasize the principal conclusions. The outer basaltic shell of the Earth was not generated at once. It consists of separate patches and strips of lava blankets. Each of them was emplaced during one of five episodes of global volcanism and may be regarded as an isolated volcanic sea, that is a basin gradually filled with a basaltic melt erupted from the interior.

The ancient volcanic seas on the Earth's surface are now

wholly continental, wholly oceanic (covered by water), or combined, continental-oceanic. In all cases, each volcanic sea was cut by deep fractures after accumulation of the principal tholeiitic basalt blanket. Volcanoes made up of alkaline basic rocks derived from deeper-seated melts rose locally along the fractures.

Any of the global episodes of volcanism on the continents took place near the uplifted fold mountains and completed a cycle of geological events responsible for mountain building. Lavas issued on the backside of the mountains, away from the direction of overturning and thrusting before this event. The folds were pushed over a foredeep in front of the mountains.

The fold mountains that bound the volcanic basin extend into the ocean floor as more or less clear submarine rises. Thus the island arcs in the western Pacific are actually fold mountains on the ocean floor, overturned and thrust outward in the arcs, towards their foredeeps. The basalts in the floor of back-arc marginal seas, as well as those on continents (in hinterlands), are completing magmatic blankets—volcanic seas in the interior of these arcuate rises.

The combined continental-oceanic lava blankets that fill volcanic seas in any of the episodes of their generation seem to be composed of lavas of different types. The tholeiitic basalts of their portions lying on the continent contain more potassium oxide. However, the topmost strata of continental blankets, eroded most easily, are identical with basalts lying at the top of the oceanic lava sequence. Being subsided, the oceanic lava sheet has preserved its upper strata made up of low-potassium tholeiitic basalts and is probably overlain by regionally extending sheets of the same type.

Having combined continental and inferred oceanic (partly lava-underlying) fold-thrust zones and uplifts generated at different geotectonic stages and together bounding the basalt provinces of relevant age, one can distinguish a pattern of active belts of the Earth (Fig. 13). The globe appears encircled by major and minor fold-thrust mountain arcs. Their age, as well as the age of the basaltic blankets in the corresponding hinterlands, is becoming younger away from the centres of Precambrian cratons, towards the median zones of the intervening fold belts. The progressively younger age of the basaltic blankets towards Atlantic-type mid-ocean-

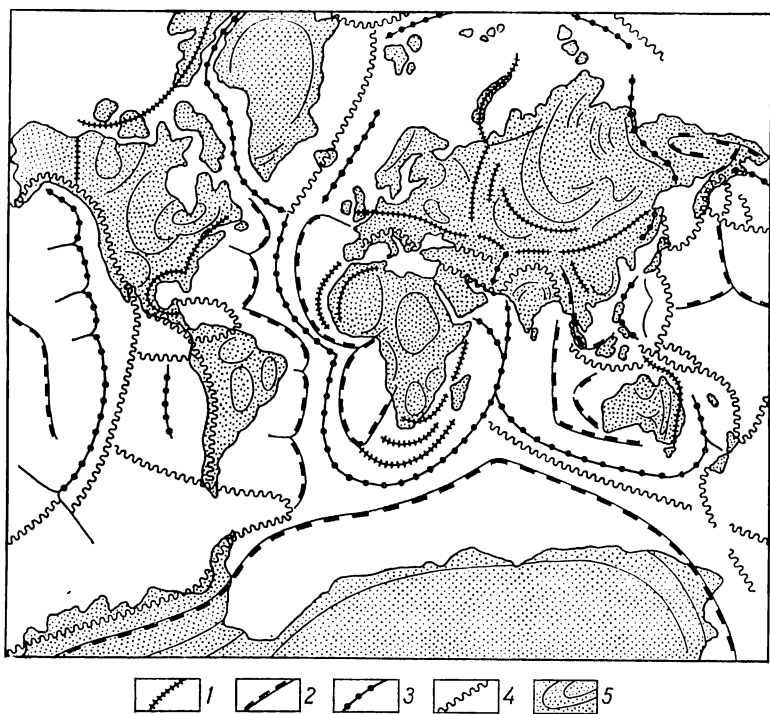


Fig. 13. Earth's orogenic zones of different ages that were responsible for the formation of the outer basaltic shell:

1—Hercynides and late Hercynides; 2—Cimmerides; 3—early Alpides; 4—Laramides; 5—trends of older fold zones in the basement beneath continental plains. Post-Laramide fold zones now at orogenic stage are not shown because no basaltic seas have yet been formed at their rear

ic ridges should reflect the same trend in the fold systems that are here entirely overlain by basalts. The youngest lavas poured out on either side of the fold zones whose fronts are linked up and which are farthest from the centres of stable cratons.

Lava Maria on the Waterless Moon

The Distribution of Volcanic Maria

Ever since 1647 when Johannes Hevelius named the dark patches on the Moon "maria", the lighter ones "swamps", and the dark-coloured low areas along the "mare" coasts "bays",

these terms have been considered arbitrary. The "islands" inside the lunar maria and the "deserts" on their coasts were also thought to be only arbitrary designations. All these terms characterized the surface albedo, i. e. the intensity of light reflection, and relative elevations of surfaces on the planet. Many scientists still emphasize that lunar maria and earth seas should not be compared, since their classification is based on different characteristics.

In the light of developments in geology, however, the term "mare", introduced by Hevelius to denote the main depressed morphostructures of the Moon, seems apt for the comparison between lunar maria and the true structure of the Earth's seas, which is recorded in the surface layer of the solid earth crust underwater. If the Moon were capable of retaining water on its surface, then water would accumulate there, as on Earth, in lunar depressions, i.e. in maria and oceans floored with volcanic basalts.

The lunar mare basins filled with basalt are 2-4 km lower than the average level of the planet's terra mass. The basins form apparent impregnations in the terra. The terra masses completely surround the maria and oceans of the Moon. The mare basins are connected with each other by "straits" with lava floors. At the same time maria are occasionally closely spaced and separated by elevated regions. The terra areas are preserved here as raised light isles connected with the major continental mass by "isthmuses" like those on Earth (Fig. 14).

Rounded lunar maria are called regular. Others are irregular. The mare regions filled with lavas are lowered relative to the surface of the surrounding terra by as much as 4 km.

Fig. 14. A schematic map of lunar volcanic maria:

1—maria with basaltic floors (MO—Mare Orientale, LV—Lacus Veris, LA—Lacus Autumni, OP—Oceanus Procellarum, SI—Sinus Iridium, H—Mare Humorum, MI—Mare Imbrium, MC—Mare Cognitum, MN—Mare Nubium, SM—Sinus Medii, MV—Mare Vaporum, F—Mare Frigoris, S—Mare Serenitatis, MT—Mare Tranquillitatis, MN—Mare Nectarum, LS—Lacus Somniorum, MC—Mare Crisium, MF—Mare Fecunditatis, MS—Mare Smythii, MM—Mare Marginis, MA—Mare Australe); 2—dots stand for axial lines of mare basin rims, heavy line denotes major rim cordilleras (CA—Carpathians, AP—Apennines, CC—Caucasus, AP—Alpes, HM—Montes Haemus, AM—Montes Altai); 3—volcanic superstructures on the basaltic floor of the Oceanus Procellarum (I—plateau Rümker, II—plateau Aristarchus, III—Marius Hills); 4—some of the largest craters (1—Aristarchus, 2—Kepler, 3—Copernicus, 4—Timocharis, 5—Archimedes) and their ejecta over basalts; 5—mare ridges of the basalt floor of maria and oceans, which continue or copy the direction of the sublava mountain rims—phantoms; 6—the areas in the western maria where underlying mass concentrations (maskons) have been established at depth

The Mare Imbrium, the largest lunar mare, would be nearly circular if it were not linked on the southwest to a huge, dark, elongated low of the Oceanus Procellarum. The basalts of these two depressions joint, thus disturbing the circular shape of the Mare Imbrium. In the northwestern Mare Imbrium the Sinus Iridium, stepping out beyond the circle, "intrudes" into the circular patch of the gigantic dark mare. The Mare Imbrium is surrounded by high terra ranges. The gently arcuate Montes Carpatius lie to the south, and farther to the southeast, across a low in the relief and along the common circle, are the Montes Apenninus. The Montes Apenninus are lower in the north, and, on the other side of a dark mare "strait" connecting the Mare Imbrium with the neighbouring Mare Serenitatis, they continue as the Montes Caucasus. The Montes Caucasus does not follow the common arc encircling the Mare Imbrium. The Montes Alpes are situated farther to the northeast, along the margin of the Mare Imbrium. These clearly linear mountains are linked as an echelon structure to the Montes Caucasus. The ranges to the north of the Alpes are random and turn southward around the Sinus Iridium.

All the ranges surrounding the Mare Imbrium are highest and their steep scarps up to 5 km high border the mare. The ranges gently descend away from the mare, reaching the average elevation of the terra. The mountains are composed of rock blocks, with signs of the slabs being shovelled towards the outer side of the convex arcuate fronts. Thick clastic units and piles of gigantic and small angular blocks occur on the gentle slopes of the mountain fronts. These features are typical of all lunar arc ranges encircling volcanic maria.

The Mare Frigoris is a dark, crescent-shaped low to the north of the terra highland. The mare is no longer circular, but it is part of a ring formed by an arcuate belt of low areas bordering the giant elevated rim of the Mare Imbrium on the north. In the west, the Mare Frigoris "flows" into the Oceanus Procellarum through the Sinus Roris.

Copying the circular form of the Mare Imbrium, the gigantic Oceanus Procellarum is also slightly curved. If we extend the arcuate direction indicated by the Mare Frigoris across the dark floor of the Oceanus and along the geometric ring formed by the outer terra side of the mare, we can observe the low Median Ridge, dividing the Oceanus Procellarum lengthwise into two halves, the western and eastern. The Median

Ridge is a series of generally parallel small swells and furrows (the ridge is described in detail by J. James). The Soviet geologists E.D. Sulidi-Kondratiev and V.V. Kozlov have long compared this ridge with the median ridges of the Earth's oceans.

By extending the arcuate depression of the Mare Frigoris over the eastern half of the Oceanus Procellarum, one can trace an almost complete ring of dark basins, surrounding the central Mare Imbrium along the outer concentric band. The Mare Serenitatis is located on a geometric extension of this band, which comprises the outer depressions. The Montes Haemus surrounding the Mare Serenitatis separates it from the marginal depressions adjacent to the Oceanus Procellarum (small circular basins of the Sinus Aestuum and the Mare Vaporum).

The Oceanus Procellarum is much wider than the continuation of the arcuate Mare Frigoris. The half of the oceanus lying west of the Median Ridge has a roughly arcuate terra margin; to the south it turns east, near the spot where both the Mare Cognitum and the Mare Nubium adjoin the Oceanus Procellarum. Farther along the circular belt, this concentric band, which is the largest dark mare filling, includes the depression of the Mare Tranquillitatis. The band joins the eastern bay of the Mare Frigoris still farther to the north. The bay is far from the Mare Imbrium, which is central in this system. Behind the Mare Frigoris and farther along the circle runs the outer ring of uplands, which extends geometrically into the Oceanus Procellarum in the form of its central ridge. The ring is sometimes called the rim of the gigantic Gargantua basin. This rim, as well as the basin itself, is concentric with the Mare Imbrium.

The mountains surrounding the Mare Tranquillitatis are less distinct, and mountain ridges as such are not visible there. Nevertheless, the Montes Haemus jut out along the northwestern margin of the mare, rimming the Mare Serenitatis. The arcuate mountain upland separating this mare on the southeast from the adjacent Mare Fecunditatis is also noticeable. The upland bends in a small arc and juts out into the Mare Tranquillitatis from the south, as if the mare basin were superimposed here on its extension (mare swell). Consequently, the southwestern part of the Mare Tranquillitatis behind this swell (the region of the Armstrong crater) belongs to another crescent-shaped low.

The northeastern Mare Tranquillitatis and the protruding dark bay to the north can also be regarded as an arcuate depression that is isolated by a sea rise and belongs to an outer (peripheral) circular low surrounding the Mare Crisium. The low also extends farther southeast to the northeastern bays of the Mare Fecunditatis, which are separated from the main part of the mare by ridges. This circular low around the Mare Crisium and, farther on, includes small dark patches of the Mare Undarum.

The Mare Fecunditatis, which at first seems circular, is composed of various dark basins filled with basalts. The most pronounced western basin is bounded by an arcuate mare rise (the Geike Ridge), which is the rim of a small circle. The westward geometric continuation of this circular rise should lie on the terra; it is not distinct there, however. The southeastern part of the Mare Fecunditatis, which lies behind the Geike Ridge running through the mare, belongs to a peculiar arcuate depression that appears to bound on the west an area with the Langrenus crater at its centre.

The Tranquillitatis and Fecunditatis maria are both composed of separate, lava-filled, arcuate depressions. Each of the depressions has its own rim. These converged rims, inundated by lavas on all sides, serve as ridges within the maria. At a distance from the raised frontal rims, the external portions of the basaltic blankets have irregular, curvilinear boundaries.

Inside each mountain ring, in the areas where the raised rim boundary is pronounced, the lavas issued as thick blankets. The blankets have uneven margins at a distance from the distinct rims, towards the centres of the individual rings. Here, the integrity of each ring disappears, and the marginal rims also become less pronounced.

Thus, the distinct, converging rims of the individual rings are located in the middle of the mare where lavas flowed out. The marginal, outer zones of every lava blanket produce the irregular, sinuous borders of such a "complex" mare. Each lava blanket does not cover the entire circular depression bounded by a mountain rim but occupies an inside position near the rim. A similar situation exists in the neighbouring depression rimmed by mountains. The convergence of these depressions results in "irregular" lunar maria, inside of which the converged rims of individual mountain rings appear as mare "ghost" rises of cordilleras called phantoms.

In "regular" maria the lavas completely fill the floor of a vast cirque inside the mountain ring; in "irregular" maria they issue near the raised circular rim. Towards the centre of their circular cirque, the lavas become thinner and pinch out along curvilinear boundaries.

Both trends in the distribution of basaltic patches can be observed in the pattern of dark lava patches in lunar terra maria (terra cirques). Typical of the second trend is the Mare Marginis, situated outside the major maria. The shape of the lava blanket in the Mare Marginis is a rough crescent whose arcuate inner part is contiguous with the southwestern terra boundary of the depression. Separate lava bays stemming from the main blanket and intruding the bordering highlands indicate that the lava extrusions were extensive only at the margin and near the mountains of a poorly defined, large cirque.

The lava blanket in the Mare Smythii is similarly asymmetrical. The lavas here fill a semicircular depression adjacent to the inner side of the western half-circle of the surrounding mountains. Along the geometrical ring in the east, the mountains disappear, as does the lava blanket. The festoonlike and curvilinear edges of eastern pinch out of lava semicircle differs from the distinct western boundary, where, behind the highland arc, the basaltic blanket is thicker. Another example of the near-marginal lava filling of a cirque is the Lacus Somniorum, which adjoins the Mare Serenitatis on the northeast and is regarded as its bay. The distinct crescent-shaped form of the dark mare is obvious here, with lavas developed mainly along the southern margin of the arched terra uplands bounding the basin. The filling of the large circular cirque Apollo, on the opposite side of the Moon, is another example of this kind. Here, the crescent-shaped lava blanket is adjacent to the southern circular mountains. A patch of dark basalts lies at the centre of this circular structure.

The lava filling arc of the Von Kármán cirque, west of the Apollo cirque, is very characteristic. The basaltic blanket runs behind and parallel to the surrounding mountains and forms a narrow half-circle.

In some cirques on the terrae, both trends of lava outflow are displayed. This is true of the Mare Imbrium region. The lava has formed, on the one hand, a marginal depression near the external limit (the Mare Frigoris) and, on the other,

a completely filled expanse in the middle of the Mare Imbrium.

The same two trends are obvious in the character of the filling in the multicircular basin of the Mare Orientale. The main lava blanket covers the central cirque inside the Montes Rook, although it is positioned asymmetrically, somewhat farther to the south. Narrow outer semi-arcuate lava depressions are also present here, however: the Lacus Veris, an elongated feature near the outer chain of the Montes Rook and, still farther from the central depression, the Lacus Autumni, a slightly curved lava blanket running along the inner margin of the Cordillera mountain chain. In the southern multicircular structure of the Mare Orientale, however, the lava blanket is uncharacteristically divided into two parts by the Montes Rook and seems to be adjacent to them. This special formation, according to the American scientist P. Schultz, is the result of the superposition of a new range, which originated with the entire mountain system, on a small ancient circular mare. Therefore, the mare blanket seems to be in an outside position, in front of the mountain range, although usually lavas fill depressions on the concave side of the ranges.

Lunar terrae have also maria where only the central depressions of the large cirques are filled. Such a depression is surrounded by an indistinct mountain ring (rim), as exemplified by the Mare Nectarus. The southwestern part of the outer range of this vast cirque, containing a centrally-positioned mare, constitutes the very slightly arcuate Montes Altai. Only on the east is the Mare Nectarus bounded by low circular mountains situated in the centre of a gigantic flat cirque.

Of peculiar interest is the filling in the Mare Australe. It is quite different from the other lunar maria. The basalts here are distributed over a vast area, whose limits along the large circle are "dotted" with the arcuate segments of mountains. It is not a continuous megacover typical of lunar maria, but separate dark patches of volcanic rocks. Most of the patches are rounded and basalts cover small shallow cirques. Some other patches are crescent-shaped, with basalts occurring within the depressions, behind the slightly raised rims. Finally, in the northeastern mare, inside a raised concentric rim, a dark lava almost fully encircles the inner, small mountain ring. The circular basaltic blanket

has the bays extending toward and even beyond the outer rim, this being an evidence of fairly large outflows along the periphery of this circular volcanic basin. There is also a tiny basaltic patch inside the small central cirque.

The patchy and thin lava filling of the Mare Australe may indicate a general pattern of how mare depressions are overlain by volcanic melt. In this mare we find a setting resembling the Earth trappean provinces with their sheets washed out "to the roots". The circular and arcuate lava patches are similar to dike "laces", i.e. trap feeding channels, on Earth. Here the systems of the dikes are separated by relics of a basaltic blanket preserved inside some of the sagged calderas.

Certainly, the principal difference is that the volcanic filling in the Mare Australe is represented only by its "lower bed". No continuous upper megacover is present here. A similar pattern in the trappean provinces on Earth develops only after exogenic factors have sufficiently eroded the layered lava blankets, wearing off and destroying its top.

The primordially meagre lava filling in the Mare Australe explains curvilinear and festoonlike margins of the inner, intracirque limits in other maria partially (and asymmetrically) filled with lavas. Lava piles are thick along the mountain rims of the basins, and they become thinner towards the centres of the cirques. It is the upper lava strata that are more likely to pinch out at a distance from the mountain arc boundaries, as their pattern resembles a small filling with only lower lava beds represented. Instead of a single basaltic blanket one can see isolated rounded patches and arcuate bands inside small individual circular rises.

So, inside gigantic concentric zones surrounding the largest rounded volcanic Mare Imbrium, in smaller circular maria, as well as inside small cirques, lava blankets covering the basins are always situated on the concave sides of the mountain rims. If there are several concentric mountain rims, each of them possesses the same regularity in lava blankets distribution.

When limited only to the inner depression of multicircular systems, lava may totally inundate that depression (the Mare Nectarus). In case a filling is incomplete, the basaltic blanket is associated with one of the sides of the central raised rim (the Mare Orientale, basalts at the southwestern ridge on the flank of the central basin). A margin of the basal-

tic blanket in the centre of the cirque displays festoonlike individual circles indicating smaller volcanic extrusions.

When not only a central depression but also the outer circular basins become filled with volcanic melt, the arcuate or crescent-shaped lava patches here also lie behind the concave outer rims (the Mare Orientale, the Lacus Somniorum, lava patches in the northeastern Mare Australe).

The same regularity is observed in cases, when the outer circular depressions of large circular maria are linked to other maria. They actually share their marginal, thickest lava fillings. This is how irregular maria appear (northeastern basins in the Mare Tranquillitatis and Mare Fecunditatis may be a filling of the outer circular basin with its centre in the Mare Crisium).

Thus, the basaltic blankets of "deep" and "shallow" lunar volcanic maria tend to be situated along the concave slopes of arcuate and circular mountains, but always inside the arc. The lavas here, issuing over a longer time than in the cirque centres, accumulate thicker blankets and sometimes run out via "straits" to the convex front of the arcuate bounding ranges. Linking of arcuate raised rims of the adjacent cirque structures, behind which thick lavas are accumulated, may produce an "irregular" mare having the inner median-type ridge completely overlain by basalts.

The Age of Lunar Basaltic Maria

Observations from the Earth have long established that lava extrusions in lunar maria are younger than terra surface. The maria are much more smooth and less disturbed with small craters resulting from the fall of small meteorites. The number of such craters on the terrae is 30 times more than on the surface of the basaltic filling of the maria. The degree of cratering (number of craters) on the Moon's surface varies: the older the surface, the more craters were discovered on it. This was used as a basis for developing a stratigraphic scheme of lunar formations, i.e. a sequence of rock origin.

It has become evident from lunar samples brought to the Earth that rocks of the Moon are very old. On the terrae they range in age from 4.1 to 3.9 thous. m.y. Main circular basins surrounded by circular mountain uplands (cirques) were formed within this interval. According to the

time of formation they are Imbrian (after the name of the Mare) or the Preimbrian. The basins of the Mare Vaporum, the Mare Nectarus, the Mare Crisium, and the Mare Serenitatis are regarded as Preimbrian. According to the recent data, these basins were formed 3.98 thous. m.y. ago.

The Imbrium basin is thought to be younger. However, recent studies of debris from the surrounding mountains put its age at 3.87 thous. m.y. According to geologist J. Head, this important result requires the whole epoch when multicircular lunar basins appeared to be less than 100 m.y.

The Mare Orientale basin is considered to be still younger than the Mare Imbrium. The time of its appearance insignificantly differs from that of the Imbrian event (the formation of the Mare Imbrium).

The study of lunar samples over the past years provided the ideas that after lunar accretion from a circumterrestrial swarm of particles the Moon could retain only a small portion of gravitational energy of this accretion. The most probable explanation, according to the Soviet geophysicist B. Yu. Levin, is a subsequent heating of the Moon owing to its higher than now rate of orbiting the Earth. The Moon's movement away from the Earth and establishment of their synchronous orbiting provide the ideas to the effect that the heating of the Moon could occur within the earliest stage of its existence as a planet.

Partial melting of lunar interior material and separation, i.e. differentiation of the melts according to composition, should have begun approximately 4.5 thous. m.y. ago. Until the great impact events which have given rise to the multicircular basins a layer of the lunar terra crust was accumulated. The crust is composed of anorthosites. They are lighter than basalts, hence the observed colour of terra surfaces. These rocks are made up of a mineral called anorthite. In Earth basaltic lavas it forms large light crystals and belongs to the group of feldspars called plagioclases. In earth basalts it crystallizes at depth and when the melt issues its crystals already exist in large aggregations among almost glassy magma material. This indicates that anorthite is a refractory mineral rapidly separated from the hot magma.

The formation of the anorthosite crust of lunar terrae was attributed to a gigantic lava "ocean" near the surface. Inside the ocean relatively low-density but already formed crystals floated up as a "slurry". A melt at depth lost a num-

ber of components taken up together with anorthite crystals. So, the composition of the anorthosite crust is generally that of basalt (anorthite is a mineral of basaltic magma), but the crust contains a smaller proportion of iron and magnesium. Mare basalts issued later were a result of a new melting of the deep-seated substance.

This conception proved to be rather consistent in accounting for many successive processes on the Moon. However, information of the past years shows that basaltic clasts available on the terrae have older ages (4.0-4.2 thous. m.y.) than anorthosites from the terra mountains. This suggests the appearance of basalts prior to the formation of main basins. Further proof is that beneath the accumulations of their ejecta there are old dark layers exposed in later impact craters. Colour and other parameters revealed that older basalts occur under ejecta in large basins. Most of the sites where these older basalts were brought to the surface, have been discovered to the north of the Mare Crisium, to the south of the Mare Imbrium and inside the Mare Australe.

Also, in the light of the studies of P. Schultz, multicircular basins came to existence after small, dark, lava-filled maria had been formed. In the southern multicircular Mare Orientale the deformation of the above mentioned small dark circle with basalts appeared concurrently with the younger circular Montes Rook. The Soviet Zond 8 photographed a site in the southern Montes Rook at a low Sun illumination angle which made it possible to identify the systems of arcuate fractures and precipices. Along the margin of the dark circle itself there is a system of vents that produced basalts filling the depression long before the Mare Orientale and its circular ranges were formed. The deformation did not affect the distribution of the volcanic vents indicating that the rim (the outer ridge of the Montes Rook) was not deposited. It looks like a bulged up and deformed substrate.

There are also specific lunar rocks called KREEP basalts. KREEP is an abbreviation for potassium (K), rare earth elements (REE), and phosphorus (P), which are abundant in the basalts. On Earth, alkalies and rare earths are usually concentrated in granites. Granites on the Moon are yet unknown, though KREEP basalts are sometimes called "lunar granites" because they are able to concentrate "granitic" elements.

KREEP rocks on the Moon are commonly represented by small glassy clasts whose composition corresponds to a basalt enriched in potassium and rare earths. The origin of these basalts sputtered by explosions is not completely clear. It was a long-standing belief that major meteorite impacts after having burst through the upper lunar anorthositic crust, eject KREEP rocks solidified at depth. They occupied their intermediate position between the feldspathic cover of the Moon and deep-seated basalt because residual basalt delivered its feldspars to the outer crust leaving the above mentioned most volatile elements in concentrations immediately beneath that crust.

Studies of KREEP glasses have revealed that they originate from a magmatic substance which should first be melted and then spattered by an explosion. So this substance is not a residual solidified mass under the anorthosite cover but a melt produced by heating. The latter cannot be attributed to impacts, as KREEP rocks have become known to overlie the already existed anorthosite mountains lacking in this substance. Should the KREEP substance result from impact explosion it would have been thrown out of the basin together with mountain-derived clasts. Melting at depth of KREEP rocks cannot be explained by means of an impact. Likewise, it is impossible to regard an instantaneous meteorite impact as the cause of the subsequent impulsive basalt filling of the basins themselves developed over a thousand million years. Each onset of basalt magmatism requires a new significant heating of the planet's depths concurrent in several regions.

The American investigator of the Moon P. Spudis emphasized that the geological position of KREEP rocks is quite definite. They appear after the formation of circular mountains but always before the basalt extrusions take place. Volcanic explosions providing the KREEP substance occurred near or directly on the mountains. At the mountain feet this substance often makes up dark covers consisting of glassy volcanic particles. These dark blankets are later flooded with lavas and, therefore, their exposures are scanty. At the same time, subsequent small meteorite impacts plough through the basalts "to their bottom", thus again ejecting the material on the surface to form a common admixture in regolith of basalt plains.

The geological position of KREEP rocks, or "lunar gran-

ites" is similar to that of earth granites. They appear after deformations giving rise to mountains but before the formation of basalts behind mountain arcs and rings. Chemical composition of KREEP rocks suggests that their melt sputtered by explosions (i.e. with volatiles participation) results from partial melting of anorthosite rocks. This also adds up to the analogy with earth granites whose origin is attributed to partial melting of thick geosynclinal piles making up orogenic zones.

As on Earth, mountain rims are the first to appear on the lunar surface. Volcanic explosions eject a KREEP substance, or "lunar granites", on and near the rims. Only after these events, basalts melted at large depths issue inside circular depressions. The formation of cordillera mountains is no longer preceding subsequent penetrations of basaltic magmas to the surface. Only small deformations occur which produce arcuate ranges on basalt maria. This can be due to an excessively high yield of volatiles during the epoch of major basin-forming episodes with which the appearance of the KREEP substance is associated.

Let us come to a question of the time of the appearance of basalt volcanic maria of the visible late basins that can be compared with the young basalt megacovers of the Earth.

Stratigraphy of basaltic lavas on the Moon, i.e. the sequence of their extrusion, has been developed much better than that of its terra areas. A method suggested by the American scientist J. Boyce is most successfully applied for subdividing basalt surfaces of differing ages. The method allows one to determine the age of small craters (diameters up to 1 km) on the surface according to a degree of their degradation. The craters are constantly destructed owing to impacts of small meteorites. If they succeeded in obliteration of rather large craters, so that the inner slopes of their lips became gentle (1°), then the micrometeorite bombardment took a long time. If only small craters were brought to the same degree of destruction, then the surface of a basaltic blanket was formed later than that of the younger lavas.

The oldest are the lavas where craters were destructed with a diameter exceeding 360 m. The youngest are those with degraded craters 140-195 m in diameter. Although this scale and an earlier one, which accounts for only a number of craters, i.e. "degree of cratering", give roughly the same results, the first is much more exact. The scale arranges relative la-

va ages, but since their absolute values at a number of sites are known from the lunar samples, it has become a real time scale. A degree of crater scarps degradation is also compared to the data on destruction of the fronts, i.e. marginal zones of large lava flows. The older the blanket extrusions, the more gentle are the scarps remaining as elevations.

Other methods of subdividing different surfaces of basaltic blankets are also applied. For example, colour and its reflection from surface at different wavelengths to a great extent characterize the basaltic composition. Darker basalts contain an increased quantity of titanium and lighter ones are low titanium. There exists rather a complicated scale allowing one to compare the intensity of reflected signals at different wavelengths.

Modern ideas about stratigraphic sequence of basaltic blankets in lunar maria were generalized by the American scientists J. Whitford-Stark and J. Head. On the basis of a detailed study of the lava filling in the Mare Imbrium and the Oceanus Procellarum four main age sequences were distinguished. They agree well with the basaltic fillings in other maria (Table 1).

Table 1. Stratigraphy of Mare Filling Basalts of the Moon (according to J. Whitford-Stark and J. Head)

Sequences (units)	Age of extrusion, thous. m. y.	Titanium oxide content	Formation in the Oceanus Procellarum
IV, the youngest	2.7 ± 0.7	Average-to-high-titanium (about 3%)	Sharp
III	3.3 ± 0.3	Intermediate titanium content (1-3%)	Hermann
II	3.6 ± 0.2	Very low-titanium (up to 2%)	Telemann
I	3.75 ± 0.05	Very high-titanium (3-5%)	Repsold

Two earlier sequences are assigned to the Imbrian system, the third, to Eratosthenian, and the youngest, to Copernican. These names are related to the identified overlying of basaltic blankets by ejecta of the large craters. These are usually bright-rayed and consist of radially excavated material. By way of example, all the Precopernican piles are overlain by the rayed ejecta deposits from the Copernicus

crater. The crater and its ejecta have similar freshness. The same applies to the Eratosthenus crater and its rayed ejecta deposits overlying all the Preeratosthenian basalts.

The returned lunar rock samples from three earlier (lower) sequences of basalts were dated for a number of sites. The youngest lava sequence younger than 3.3 thous. m.y. (variance is assumed to be ± 0.3 thous. m.y.) have not yet been sampled. However, relative youth of the corresponding basalts appears to be sufficiently proved by a number of characteristics.

The correlation of single-aged (as measured by modern techniques) basaltic blankets, which appeared simultaneously in different and far-apart lunar maria, is of extreme significance. In various lunar basins there are lava blankets degraded by meteorite bombardment to an equal degree. The blanket surfaces also have the same relationships with the ejecta of the earlier craters (the clasts overlain) and with those of the younger craters (overlain with the clasts). High-accuracy measurements applied to all the maria on equal terms, reveal differently aged lava piles convincingly enough.

It should be emphasized that fields of basalts differing in age are discrete. The entire surface inside them displays uniform features. "Gradual" change of the surface types within such fields has not been identified. Sometimes the younger lavas superimpose the fields of much older lavas with no "intermediate" blankets present. In cases when very old lavas contact very young ones, returned (reflected) signals at certain wavelengths appear to be blurred. However, such sites are always known.

The studies of D. Wilhelm based on TV and photography mapping have shown that rock types of various compositions occur in each age range of lavas but they have different volumes.

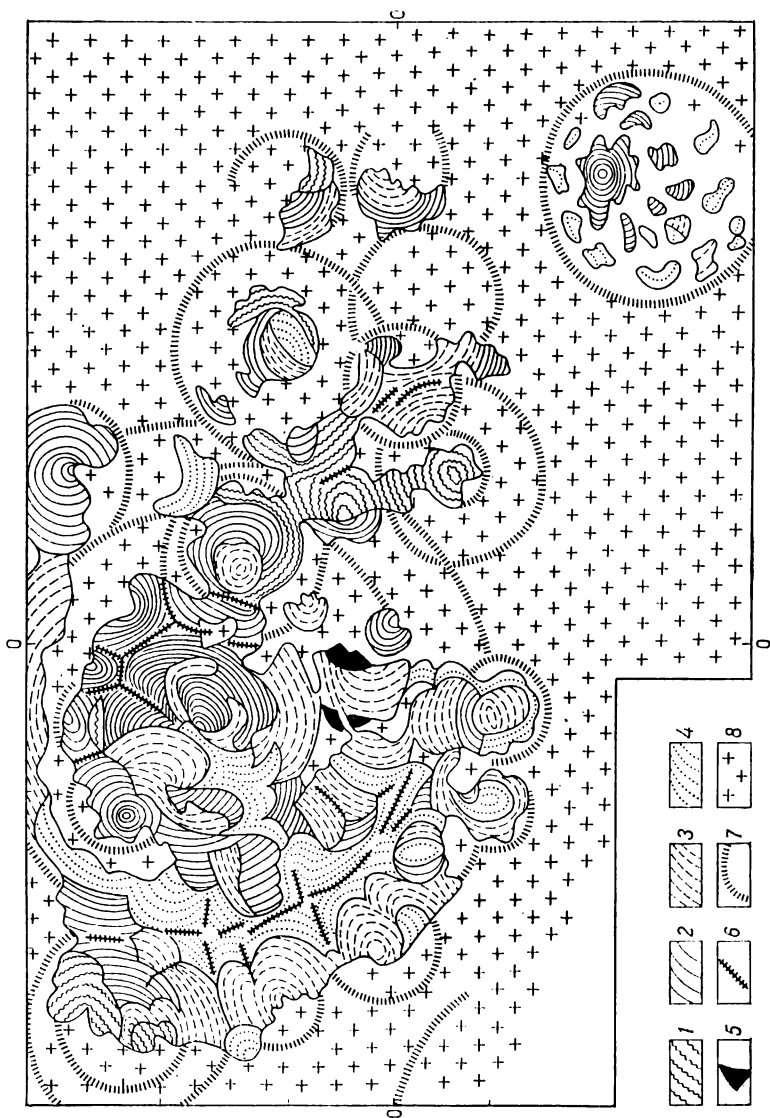
After the appearance of large multicircular basins the epoch of "filling the maria" (the late epoch) has begun on the Moon. Lavas began to flow onto the surface inside rounded basins. The subsequent lava filling of the maria continued for about one thous. m.y. Toward the surface lava penetration occurred in separate outbreaks—impulses. Each impulse records a global heating up of the planet, because lavas issued at many sites. At the same time the impulses were

regional in extent, as in each of the lunar maria the lava sequences are not fully represented.

The intervals dividing global impulses of the lunar basaltic volcanism are very long, between 150 and 600 m.y. More detailed subsequences within these intervals, if found, should only be an additional argument in favour of the multitude of stages in heating up and melting of the lunar interior that supplied lava to the surface. Such a prolonged influence on the natural development of the planet is difficult to explain as being due to the instantaneous impacts produced even by very large meteorite bodies. Synchronous epochs of lava extrusions in different maria make it more reasonable to assume that the formation of the basins and their subsequent impulse-affected lava filling was determined by endogenic activity of the Moon. The process continued till the energy has been almost completely spent.

Let us consider how lava blankets of different ages are distributed over the floor of the late volcanic lunar maria and oceans (Fig. 15). The largest exposures on the surface of the oldest basaltic unit I are known in the "irregular" Mare Tranquillitatis, composed of depressions, which are concentric relative to the adjacent circular maria, and in the Mare Nectarus. The same unit I come to surface in marginal parts of the Crisium, Smythii, Marginis, and Serenitatis maria. Its separate fields are discovered in raised marginal sites of the Mare Imbrium. It may be more widely developed here but is covered by young lavas. Finally, it is exposed in the north-western Oceanus Procellarum and, in the form of small patches, on the uplands of its southern portion.

The basaltic unit II, resulting from a global impulse of magmatism, composes large lava exposures in the central and eastern Mare Serenitatis, in marginal parts of the Fecunditatis, Crisium, and Smythii maria. It is a large field in the northeastern and the northern Mare Imbrium. Its small flows are typical of the southern Oceanus Procellarum. These basalts make up the largest lava field in the Mare Australe. This unit in the Mare Crisium seems not to have covered the basin completely and it is concentrated in the eastern part, because larger craters to the west beneath the younger lavas exposed only the oldest unit I. In the Oceanus Procellarum the unit II did not completely overlies the basin too, since not far from the main field of these lavas in the



northern Oceanus, the zones were identified, where the younger lavas overlie the oldest ones.

The basaltic unit III of the lunar impulse of volcanism almost completely covers the Mare Fecunditatis, the western parts of the Crisium and Marginis maria, and the inner western circle of the Mare Serenitatis. The basaltic blanket of this age is developed on the surface of the Mare Imbrium, in its western and southern near-marginal parts, and occurs on the surface of the western periphery of the Oceanus Procellarum. Lava patches of this age circle the area where the unit II is developed.

The youngest lavas on the Moon (IV) make up finally the eastern semicircle amidst the Mare Crisium, extreme northern bays of the Mare Serenitatis, and form the western marginal crescent-shaped belt in the Mare Imbrium. They run across the centre and partly in the eastern expanse of the Oceanus Procellarum also forming small patches in its extreme west. Rounded and crescent-shaped areas of young basalts compose a peripheral ring of lava patches in the Mare Australe.

Younger lavas occupy more successively marginal basinal areas in circular "regular" maria. This is particularly typical of the Serenitatis and Imbrium maria, and a crescent-shaped lava field in the Mare Marginis. The same trend is observed for the Mare Humorum (with successive blankets being displaced farther to the north), and for the Mare Nubium (westward and eastward displacements).

Referring to the Mare Australe R. De Hon noted that eruption centres are invariably displaced towards the cirque maria periphery. The same applies to other circular maria. Individual inner basins bounded by mare ridges are formed prior to being filled with younger lavas. It is clearly demonstrated by every small lava patch in the Mare Australe, eastern Mare Crisium (with lavas reaching only up to its Median Ridge), Mare Serenitatis where a young lava blanket is terminated by an upland on the east. The regularity is somewhat less distinct in the Mare Imbrium, although the

Fig. 15. The age of basalts inside volcanic maria of the Moon:

1-4—basalts; 1—extrusion phase I (3.9-3.75 thous. m.y.); 2—extrusion phase II (3.75-3.6 thous. m.y.); 3—extrusion phase III (3.6-3.0 thous. m.y.); 4—extrusion phase IV (3.0-2.7 thous.m.y.); 5—"dark blankets" (luff-like KREEP rocks) formed during volcanic explosions; 6—median oceanic ridges; 7—terra mountain arcs; 8—terrae

form of the field boundaries in the basin's extreme southwest also suggests that the poured out melts were bounded by an arcuate upland.

Peculiar is the zonality of lava blankets of different ages inside the Oceanus Procellarum. In its middle the youngest basalts are found in a vast lengthy field and separate crescent-shaped patches in the south along a median system of mare ridges and grooves. Older lavas are exposed inside the ridges arcuately bordering the lava field fronts. A young basaltic field extends along the Median Ridge of the Oceanus farther northwards where it is merging a blanket of the same age in the arcuate Mare Frigoris.

In the Oceanus Procellarum, the most "irregular" volcanic basin on the Moon, another law is determined, that suggesting lava "rejuvenation" towards the centre where the Median Ridge contains a system of small ridges and grooves. This rejuvenation results from separate pulsations, each one producing an entirely new basaltic field. It will be recalled that here, as in other volcanic maria of the Moon, all the indications of lava age sharply change on the boundaries of basaltic blankets.

The Median Ridge of the Oceanus Procellarum can be regarded as a submerged rim of the huge ring, an element of the multicircular Gargantua basin with its centre in the Mare Imbrium. Then inside and on this megacircular rim there is the youngest basaltic blanket continuing in the northern arcuate Mare Frigoris. In the western periphery of the Oceanus separate patches of similar young lavas also occur along the margin of the outer mountain terra surroundings. Lavas in the western Oceanus do not form a continuous band, they constitute separate blankets encircled by their own small cordilleras. This is typical of the areas where volcanic cover is insignificant. If the impulse of basaltic extrusions is weak, only small lava patches are to be formed.

Each subsequent impulse of basaltic extrusion in circular lunar basins occurs progressively farther from their centres. This "retreat" is accompanied by gradually decreasing volume of the melted material brought to the surface. The same law is also revealed in small circular maria where later lavas are concentrated along one of the margins of the surrounding mountain ring.

So, the mare-type basaltic lavas had issued on the Moon

before the main multicircular basins were formed. In 1980 J. Whitford-Stark and J. Head presented data to the effect that there are varieties of "prebasin" basalts with different titanium content and age of about 3.9 thous. m.y. (the fragments in samples collected by Apollo 16 and 17). Such Pre-Imbrian basalts having peculiar differences in their compositions cover large areas. This means that extrusions of lunar maria lavas did not necessarily follow the assumed major bombardment; they also occurred earlier. Some older extrusions inside large basins to be formed later had been concurrent with the development of the youngest basin (Mare Orientale).

Could large meteorites simply interrupt the general course of basaltic magmatism on the Moon by creating impact ejecta depressions—"excavation basins" within the interval 3.98-3.87 thous. m.y.? However, the Post-Imbrian mare basalt issued precisely within their limits. It cannot be explained by a low floor of the basins. General-type lavas appeared in the nearly-flat Mare Australe practically lacking a mountain ring. Besides, everywhere young basaltic flows are removed farther from the centres, this rule is similar in small and large circles.

It is impossible to separate lava extrusions from concentric circular inhomogeneities of the planet. The lavas themselves display concentric zoning of successive upward breakthroughs. The largest and smallest basaltic patches in maria and terrae are always located near large or small arcuate and ringed mountains. The basalts do not flow out outside the rear zone of a large or small raised arc of either a terra or maria. Through merging, superimposing or sharing their margins, circular or crescent-shaped basaltic patches inside mountain arcs or rings form uninterrupted lava blankets of lunar mare depressions.

A more plausible explanation is that gigantic mountain rings, together with small mountain arcs flooded by lavas, have also resulted from endogenic planetary activity. Its most powerful explosions would give rise to huge mountain rings, with inner circles being ploughed out by instantaneous release of volatiles (water and gases). They cannot be retained by the Moon because of its small mass. The bulged-up lunar substrate has formed the "fixed waves" of mountains ringing the excavation depressions.

The American scientists believe the concentric fixed rises

may result from the so-called "basic wave" produced by a shock of the solid planetary crust. It may be caused by exogenic (meteoritic) as well as inner (endogenic) influence. Both give rise to an explosion. Ejecta provided by a gigantic endogenic explosion can also lead to the appearance of secondary craters, positioned radially relative to the epicentre. The endogenic activation of the rims continued for as long as a thousand million years after the principal explosions expulsion of volatiles from main basins had taken place. But it was only in the form of zonal, basaltic melts delivered from the interior "dried" in the above way. Substrate movements prior to each volcanic pulsation formed small mare ridges bordering later lava basins.

Thus, the following can provide an answer to the question as to when basalts of the Moon flowed out. Earlier basaltic extrusions (up to 4.0 thous. m.y.) preceded the main "basin-forming" events. After large multicircular basins had been formed, and partly concurrently with their formation (3.97-3.87 thous. m.y.), began the stage of late successive basaltic extrusions continuing up to 3.0-2.5 thous. m.y. ago.

The basalts issued on the surface in four main successive global outbursts of volcanism. They filled visible volcanic maria of the Moon. Each outburst formed patches, bands or crescent-shaped zones filled with basaltic blankets in maria of the Moon. A depression bounded by the arcuate or ring rise (barrier) had been formed before each successive outburst of eruptions. The lavas issuing during eruption accumulated inside the isolated basin.

The same regularity of gradual successive basaltic flow is observed in every large circular basin. Each consecutive outburst of volcanism moves lava eruptions farther away from the centre toward the margin. Young volcanic blankets lie closer to the periphery of the basins, approaching their border formed by arcuate mountain rises.

If neighbouring big and small concentric bands link each other, the youngest basalts appear simultaneously on both sides of the raised rim, shared by these bands. As a result, the common rim consisting of converged mountain arcs then becomes the Median Ridge of an "irregular" mare. As the youngest basalts cover the ridge, it becomes a "ghost" of arcuate cordilleras called a phantom.

Ridges and Grooves on the Floor of Lunar Maria

Mare ridges rise to 300-450 m relative to adjacent plains and extend in separate fragments whose length averages 50-70 km; some ridges are as long as 100-150 km. Their width averages 4-5 km, but there are some with steep sides and about one kilometer wide.

In the maria an average magnitude of "ridge-type" relief varies within 50-350 m. These are separate raised arcuate fragments with jagged summits. Anticlinal lava occurrence has been proved for many mare ridges—they are folds convexing upward. However, this does not reveal the origin of ridges.

R. Greeley and P. Spudis, the American students of the Moon, compared the morphology of lunar mare ridges with ranges of the trap Columbia Plateau in the Cordilleras. They arrived at the conclusion that both have similar features in size and morphology.

Special geophysical methods used to study subsurface layers in the Serenitatis and Crisium maria have shown that lavas here form members, i.e. 1-2 km thick blankets separated by less dense interlayers. The surface of deep layers is so pushed along the ridges that this infers flat thrusting deformations. Blocks in the ridges move vertically and horizontally. The ridges fringe basins inside the maria themselves and run parallel to the margins of individual circular basins making up these maria. Such basins in irregular maria contain mascons (mass concentrations), i.e. the areas, where interior compaction has been found under the surface. Usually the mascons are characteristic of the centres of the circular maria, where most of the heavy basaltic lavas are accumulated. The mascons are also being tied to dense planetesimals buried during the accretion of the Moon.

Ridges parallel to outer margins of circular basins are very well represented in the Mare Serenitatis. An important feature is that the ridges continuing over the margins of this mare join the surrounding mountains. This confirms a fault origin of the ridges.

The faults should be rather deep, cutting through highly raised continental scarps. They are not small near-surface

displacements resembling a caldera-type subsidence occurring when great thicknesses of lavas come from "emptied" subsurface chambers.

Other scientists (for example, D. Warral and co-authors) believe that orientation of ridges—folds in circular basins is not related to the floor relief and basin filling. According to this view, ridges result from a compression, including total compression of the planet, as even in circular maria they are mostly oriented in the northern direction.

The origin of mare ridges is explained in several ways.

1. They resulted from squeezing the underlying rocks by basins sunk under lava weight. Many ridges coincide with zones where basalt thickness changes.

2. The ridges are intrusive bodies, which moved through fissures and pushed the lava roof upward.

3. They are analogues of the Earth's ridges formed by compression producing thrusts. This opinion has a backing in that many ridges have a sharply asymmetric profile. Thus, in the area of the Taurus-Littrow Valley of the eastern Mare Serenitatis there is a mare rift parallel to the basin boundary. A small crater was formed in the basin surface along a fault. A preserved half of the crater is on the western side of the ridge and the other one has "disappeared" under a shovelled slab. Such relationships are indicative of the lava slabs always being shovelled towards the outer side of the ridge convexity. The lavas were evidently solid and there are preserved pits from impact craters on their surface. The American geologist P. Schmitt who had landed in this area of the Moon with the Apollo 17 mission discovered that the mare ridge continues as a terra fault, and this confirms its tectonic origin. Similar ridges are also observed in other maria.

4. Mare ridges are systems of dykes having supplied lava during the latest phases of mare filling. Above such channels lava forms rampart-shaped swells on the surface inside which molten magma continues to flow along a pipe after the walls of this "channel" had already hardened. A cavity left behind by the lava may subside. Its roof would then collapse and the swell would become a narrow depression. Such depressions are called rilles. As the swells-ridges sometimes are replaced by rilles, continuing each other, such an explanation of the origin of certain mare ridges is quite plausible.

5. Ridges copy underlying structures of the pre-lava relief. These assumptions are also sufficiently justified in many cases. For example, inside irregular maria, ridges-rims concentric to different circular basins are undoubtedly indicative of such relief. The ridges corresponding to a sharp change in lava thickness are essentially the features of the pre-lava topography, though some steps (slope distortions) result from later "renovations".

Radar inspection from near-moon orbits has revealed subsurface layers of basalts in the maria. It has also shown that an average depth of reflecting surfaces is 1-2 km. In the Serenitatis there are two such layers overlying the third, deeper one, and one layer in the Mare Crisium. Separating surfaces are interlayers of less dense rocks, being either destructed regolith above lower lava strata or a mantling tuff-like material supplied by individual volcanic explosions.

Radar study of the Mare Serenitatis has shown that impacts from small bodies creating tiny craters do not change the deformation of the layers (thus also confirming the meteoritic origin of such craters). At the same time, along ridges and adjacent grabens (tectonic rilles) both upper and lower layers are similarly displaced. This confirms their tectonic origin, i.e. blocks were moved up and down by means of endogenic forces. It is important that basalt layers in all near-surface strata become somewhat thinner towards the mare ridge axes, indicating a continuous and new development of block movements in different epochs of lava accumulation. On the other hand, a considerable curvature of layers along ridges can be seen on profiles constructed according to radar-derived data. Deeper lava strata probably come to the surface in the crests, i.e. ridge axes.

Thus, old lavas of the Mare Crisium appear in the axial zone of a ridge concentric to the southern marginal scarp of the mountain surroundings. A narrow arcuate outcrop of old lavas underlying a younger blanket indicates that the ridge had already been raised in relief by the time the upper mantle issued. Young lavas pouring into the basin flowed around rises and did not cover the ridge crest.

A lava complex on the surface of the ridge may give an indication as to what strata occur at depth. In particular, it has been discovered that under the youngest basaltic blanket in the southern basin of the Mare Crisium there are no "intermediate" lavas (III) that are developed in the north-

western mare. On the other hand, in its northwestern part, where the youngest lavas have not issued, the strata II can be lacking, whereas it is widely developed in the eastern mare and exposed in the mare southern ridge.

Studies of mare subsurface layers by radars also made it possible to confirm the thrust origin of mare ridges assumed from asymmetric forms of the ridge profiles. For example, a rise of lower lava strata was traced towards a ridge in the southeastern Mare Serenitatis. On the outer, convex side of the ridge a fault was revealed in subsurface lava units. Relative displacement of two blocks along the fault amounts to 300 m. However, on the outer side of the convex arc of this ridge the fault and displacement of layers are not shown in the relief. According to the American students (R. Filipis et al.), such observations confirm a hypothesis by V. Lucchitta to the effect that deep-seated vertical faults become flat-dipping thrust faults in the near-surface layers of mare ridges.

Rilles of complex, curvilinear shape (to be described in the next chapter) have the volcanic origin. Others are straight or arcuate with sharp boundaries. These are tectonic rilles, or subsidence grabens. The American geologist M. Golombek noted in 1979 that straight and arcuate grabens are usually bounded by faults dipping towards the centre at an angle of 60° . Their average depth is less than 1 km, width 2 to 3 km. Graben walls and floor have similar constitutions, indicating the sinking of narrow blocks. If mare grabens extend onto a continent they become wider and deeper (up to 3 km), which demonstrates a thicker loose and crushed layer on the terra surface. Almost all grabens occur on mare margins, where they are usually concentric and form common systems together with mare ridges. Outside the margins, in the mountains, they are also concentric and before the mountain fronts often lie radially to them (Fig. 16).

V. Lucchitta and J. Watkins have shown that 35% of all flat-bottom and more than 10 km long lunar grabens are located in volcanic maria. Out of this number 90% occur on basaltic blankets I and II, i.e. have ages older than 3.3 thous. m.y., and only 2% on young basalts. The remaining 8% have unknown age.

At the boundary of young lava blankets they overlie grabens. Tectonic, fault-producing movements continue much

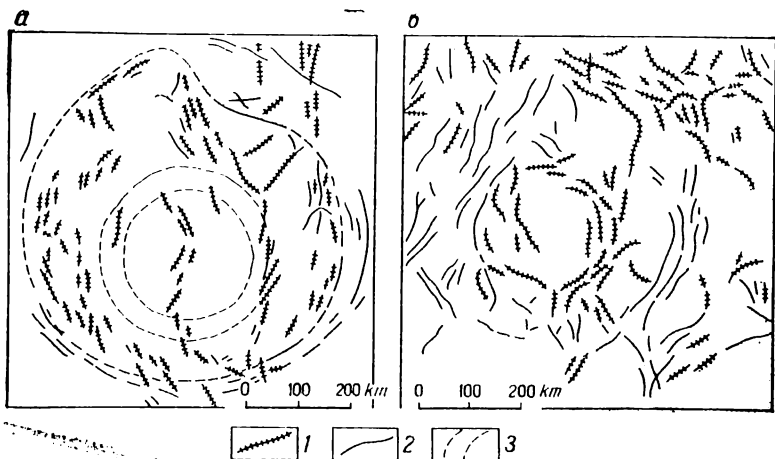


Fig. 16. Ridges and grooves of the Mare Serenitatis (a) and Mare Humorum (b):

1—ridges; 2—grooves; tectonic rilles; 3—axial lines of mare basin rims

later than basin-forming processes but their intensity becomes decreased.

Grabens also occur on the margins of maria possessing mascons. Very characteristic are the systems of grabens and ridges surrounding the Mare Serenitatis studied in detail by the geologist Solomon in 1979. Distinguished here is the 50-100-km wide system of ridges and grabens bending parallel to the mare margin. Sometimes the grabens are separated by flat-dipping mare swells that differ from narrow ridges which are often asymmetric and have narrow margins. Precisely in this mare a regularity was determined to the effect that young lava blankets are bounded by the systems of grabens and ridges bordering lava basins. At the same time the young blankets themselves are disturbed insignificantly. Before young lavas filling a depression its boundaries have been already formed by tectonic movements. Later the substrate under lavas continues to sink, the ridges appear, but grabens are rare.

As grabens and ridges clearly occur on the margins of mascon circular basins surrounded by mountains, the system of ridges and grabens is of specific interest in the centre of the Oceanus Procellarum. Here mascons are absent, although the youngest basalts are developed. Apparently, the centre

is devoid of thick lavas. There are some mass concentrations (mascons), east of the Oceanus ridge (in its centre) and west of it (to the south). The fields of young basalts IV both on the west and east from the ridge are broken down into separate semicircles bordered along their fronts by a system of narrow ridges and grabens. These are the youngest basaltic blankets that come on both sides to the margins of a common limb of individual mascon basins of the Oceanus Procellarum. Older basalts (III and II) are exposed in central ridges of arcuate uplands.

The system of the Median Ridge of the Oceanus Procellarum, with the youngest lavas in the centre, resembles the zone where two large arcuate basement rises link each other. Behind each of them, mass concentrations appear on two sides of the Median Ridge. Its arcuate elements bounding the converged young lava blankets, similar to those in circular basins, are fresher additions to the structures of the sublava substrate rises.

Thus, on the floor of lunar basaltic maria and oceans there exist tectonic (i.e. produced by endogenic processes) ridges and grabens. They are arranged into common systems as on the Earth's volcanic blankets of continents and ocean floor. Many arcuate ridges are asymmetric, with thrusting towards the outer side and appear as raised barriers (rims) for younger lava basins. The ridges are similar to the Earth's island arcs where old lavas of ocean floor participate in thrust rises bordering "transarcuate" basins. Basalts in such inner basins bounded by a thrust rim are always young. They issued after the uplifting of an island barrier (rim). The ridges where older lavas are curved and raised, as well as tectonic rilles (grabens) bordering these ridges, as on Earth, occur not only on the margin but also in the centre of lunar basaltic oceans. They correspond here to the converged arcuate rises of the pre-lava basement.

How Lunar Maria Were Formed!

The Moon's interior is believed to have initially contained a smaller amount of volatile components in comparison with the Earth's. Nevertheless, a very rapid pressure drop in magma approaching lunar surface should internally release gaseous bubbles with carbon monoxide and hydrogen as their chief components. The more bubbles are produced in magma,

the faster is its outflow. A rate of basaltic lava outflow on Moon is considered three or even ten times as high as that on Earth. On the surface, lunar lava, rapidly losing its volatile components, should solidify much faster than on Earth. At the same time, viscous friction inside the lava flow warms it, which, according to L. Wilson and J. Head, may help the lava to move along slightly sloping surfaces for a long time.

Eruptions in volcanic maria are considered to belong to the fissure type; the direction of lava flows is determined by relief. The directions in some areas are known to have been different from modern slopes of the surface, indicating later settlements of the central parts of basins.

Rapid arrival of low-viscous lava in large quantities enabled basalts to spread over vast areas, forming flat surfaces and filling small rounded depressions. Precisely because of this, deformations of lava surfaces are usually secondary, produced by tectonics.

Sinuuous volcanic rilles are eruption channels visible on the surface. They have characteristic segments, differently oriented and possibly corresponding to fissures at depth (small bends exist even inside segments). When lava issued out through such channels, an upper boundary of the flows solidified in the form of a pipe, then its roof collapsed. Rilles are considered to be typical of relatively late phases of extrusions when most of the volatile components were taken away by first portions of the melt.

Studies by A. Gifford and F. El-Baz have shown that the average height of scarps on the front of lunar basalt flows is about 20 m, probably less than their thickness. The height of 57% of the measured fronts exceeds 15 m and that of 27% is below 10 m. The fronts of the youngest blankets in the Mare Imbrium are as high as 100 m. Huge flows of young lavas in the southwestern Mare Imbrium issued out of a fissure extending from a crater on the mountain named after the Soviet Academician Vinogradov who contributed much to the study of lunar rocks.

There are also bigger craters on the Mare Imbrium flows considered to be the youngest on the basis of the topography and number of small craters. A relative excess of such big craters suggests that some fresh craters (with the diameter exceeding 225 m) is of clearly endogenic, i.e. volcanic origin.

Analysing the fields of surface lavas in the Mare Imbrium, A. Gifford and F. El-Baz noted that blankets of similar age should have many sources, i.e. slder channels. Besides, in later flows preserved are not only the walls of rilles, but also the frontal scarps of flows. Poorly expressed frontal scarps of old lava sequences (I, II, III) are caused by their destruction, degradation. A scarp 15 m high can be completely destroyed or lowered by temperature changes or small meteorite bombardment forming a regolith blanket near the scarp.

There are few volcanic craters, domes, and rilles on lunar maria. Therefore, most of slder channels are considered to be mantled. They are evidently also present in the Mare Australe under the basalts of small circular basins, as these are not connected by "straits", which could have supplied lava from one small depression to another.

Considering the sources and style of lava extrusions in the Oceanus Procellarum, J. Whitford-Stark and J. Head note that it is very rarely that channels in the form of sinuous rilles and low cones (about 10 km in diameter) are observed in the youngest lavas (IV). A thickness of all flows of this unit is limited to 100 m as mare ridges (with outcrops of older lavas) form barriers separating basins from each other. The thickness of individual flows averages 10 m, but some are 25 m thick. As the lavas of this age have identical known parameters, it should be emphasized that isolated magma chambers developed similarly to separate fields having their own sources covered by blankets.

Much of the lava III arrived from an inner upland (the Montes Rümker) in the northern Oceanus Procellarum, though there should be also local sources in other parts of the lava field. The unit III in the Montes Rümker is assumed to be thicker than the youngest lavas lying above. This unit is more than 200 m thick on the ridges separating the fields of young basalts in the central Oceanus.

The lava unit II is marked by many individual sources that originate from the Montes Rümker, but most of them are located in more southern uplands, i.e. the Aristarchus Plateau and Marius Hills. The latter upland lies on the Mid-Oceanic Ridge. The lava sources on uplands are characterized by rilles "topped" by central crater-pits, the most long suppliers of melts. The diameters of such craters exceed 5 km. Large curvilinear rilles, channels supplying later flows,

are as wide as 1 km. The average thickness of the unit II is about 250 m, sometimes it reaches 500 m.

The unit I, the oldest in the Ocean, has the least thickness (averaging 125 m). It apparently filled the Ocean insignificantly.

One of the most important observations on the Oceanus Procellarum filling concerns the appearance of the so-called dark blankets at the base of the lowest unit. They are considered to be volcanic ashes and tuffs resulting from explosions. It has been recorded that such volcanic products are associated only with accumulations of two lower units and especially with the lowermost one. It is a further demonstration that the content of volatile components in subsurface chambers where the melts are formed decreases as basaltic volcanism progresses from the earliest to the latest phases. Thus, similarly to volcanic blankets of the Earth's basaltic seas, lunar lava basins are being filled when the melts issue from numerous small fissures. These are overlain by basaltic blankets and become invisible. Continuous lava outflows stemming from separate centres result in that at the end of effusions appear sinuous volcanic rilles. Where such later lava sources come together, there appear the "tops" of rilles, i.e. small rounded calderas. The areas of lava accumulations near eruption centres protrude as volcanic superstructures in the relief of basaltic blankets.

Volcanic Maria of Planets Behind

Arcuate Mountains

Volcanic Seas of the Earth and the Moon Have Similar Constitution

Volcanic maria on Earth and Moon would always appear after the rise of mountains bordering the lava basins along the arc or ring. Upon more close examination, the young lava cover of the Earth (its basaltic shell), reveals its "scaly" constitution. Each "scale" is a basaltic blanket of a certain age. Being superimposed on each other, basaltic slabs of successive stages of development gradually overlay the entire floor of the Earth's oceans.

The oldest basaltic blankets (slabs) occur in the near-coastal Atlantic, younger ones appear towards its centre. This shows that mountain systems, behind which basalts issued, also were becoming successively younger, retreating from central parts of old continental platforms. On continents the oldest stable blocks are naturally being surrounded by fold zones of successive stages of mountain formation. This regularity has long been revealed. It is also typical of the ocean floor and expressed in a changing age of basaltic fields that were gradually covering fold systems from behind. The youngest are those situated in the centre of Atlantic-type oceans.

A basaltic blanket appearing behind the newly born mountains sinks the whole area beneath it. The subsidence does not immediately reach the level of the ocean floor. For instance, the trans-Urals and Western Siberia experienced a substantial lowering with the subsequent formation of a huge young platform—"an abortive ocean". At the same time, the area of the platform covered by the Tunguska traps first subsided during the lava extrusion stage and then rose, as did a number of other trap-covered platforms, such as the Deccan Plateau of Hindustan and the plateau of the Parana River basin in South America. The subsequent rises of the lava blankets caused their covers to wear down producing stepped slopes of the elevated plateaus.

The process of post-basalt sinking is most stable near the surrounding mountains, where lava blankets overlay the regions heated and injected by granites during the epochs of folding and mountain formation. The cause is that the "hot basaltic blanket" placed on top of a crustal block already greatly warmed up will induce further heating and more stable release of volatile components in the lithosphere, particularly, that of water.

A substantial warming up of the earth at small depths under basaltic blankets is ascertained by the fact that the coals of productive masses often lied on continents under the traps are transformed into anthracites. In the coal-bearing basins with no lavas on the surface such a process occurs at depths of 10 to 15 km. According to the Soviet geologists A. K. Matveev and Yu. R. Mazon, the coals below basalts are transformed into anthracites at depth up to 4.5 km.

Deep-sea drilling at the mouth of Bay of California in the area of young basaltic volcanism revealed that temperatures of sedimentary layers between the young intrusions of

basic plutons reach as high as 200 °C at depth of about 1 km. Similar temperatures under lava blankets are calculated for previous epochs.

The lithosphere beneath basalts becomes more compact, and due to intensive warming up the Earth's crust acquires the properties similar to the density of the oceanic crust. Water seems to squeeze out of the earth and is supplied to the surface, where it is concentrated in the water layer. It is one of the alternatives for the so-called "geophysical oceanization" of the Earth's crust showing how it acquires new density characteristics determined according to seismic waves velocities.

G.D. Afanasyev, a prominent Soviet geologist also attached great importance to the appearance of a surface (oceanic) water layer, assuming such a process of the Earth's crust oceanization. He believed that the water pumped out of the interior creates an additional downward pressure.

Even with no water layer on the Moon its basaltic areas possess a relatively thin (about 50 km) and compacted crust as compared to the one beneath lunar terrae (about 100 km). Therefore, if planetary crusts are compacted due to their overheating by deep-seated "source" from below and "hot blanket" of surface lavas from above, this compaction alone is sufficient to produce new crustal characteristics. Densities of layers beneath basalts are not affected by presence or absence of water on basaltic basins, below which the planet's solid mass sagged down. At the same time, a degree of "drying" of underlying basalts should depend on the thickness of issued lavas. In the vicinity of mountains, where a lava blanket pinches out, warming up is not so effective either. Thus, the Ural Mountains remained raised as well as the Appalachian Mountains on the margin of the North American continent though their rear zones subsided under lavas. The single-action formation of the 1-1.5 km thick basalt blanket on platforms does not necessarily cause an adequate compaction of their relatively cold interior. Therefore, its cooling follows the period of magmatism. Volatile components release insufficiently and platforms bulge up once more. Note that the latest lavas of trap continental provinces are most similar to low-potassium oceanic basalts. It is such basalts typical of the ocean floor whose thickness can indicate the extent of "geophysical oceanization" of the Earth's crust.

The "drying" of the interior is also dependent on adjacent regions of volcanism. Basaltic blankets adjoin each other and their margins are superimposed. The effect of the initial warming up is enhanced by a subsequent magmatic impulse. The phase of lava extrusion on Earth (always occurring near a zero surface level) and the phase of platform rise accompanied by faulting and superstructuring volcanic masses (see Fig. 11) are usually separated by 20-30 m.y. If the adjacent area at this time witnesses basalt extrusions of the next global epoch, this additional warming up again intensifies the process of "drying" the substratum beneath basalt till it reaches a certain critical state. Thereafter, the crustal block becomes stable, although at a low (ocean hypsometric) level.

On the Moon the most high-density subsurface areas are characterized by mascons. These are typical of circular maria and especially those areas where lavas issued in the course of several magmatic epochs. However, mascons are also present beneath the circular basins devoid of lavas on the surface, but with possible large intrusive magmatic bodies. Such circular basins called thalassoids are typical of the invisible hemisphere. On the near side, mascons appear in the areas of circular maria where the youngest lavas are identified on the surface. Usually they are underlain by older basaltic blankets, i.e. thickness of lavas is greatest here.

In any circular mare of the Moon each subsequent magmatic impulse occurs in a still narrower band or in a separate small basin which appears in the blanket of older lavas. The margins of such a young lava basin are usually made up of mare ridges with raised old lavas. These individual rims first bulge up, and then follows the extrusion of young lavas inside the depressions isolated by the rims.

Almost the same succession can be observed on Earth in a gigantic rounded basaltic basin of the Pacific Ocean. The vast central region is filled with its oldest lavas. Following the formation of arcuate island rises of the early Alpine fold mountains (at the turn of the Jurassic and Cretaceous), Upper Cretaceous-Paleogene basaltic blankets were formed behind the arcs. They appeared on the Ocean's margins as separate patches behind the fold arcs in the west and along a huge arc over the edge of the East Pacific Rise in the south and east. The next (Laramian) phase in the formation of fold island arcs at the turn of the Cretaceous and Paleogene re-

sulted in deformation of an old blanket of the Ocean's floor. The new mountain arcs separated the youngest lava basins where Neogene basalts issued. In the west, this was again accompanied by the isolation of small individual concentric bands surrounded by ocean mountain arcs; in the south-eastern Ocean once more appeared a huge arcuate belt of lavas reaching the North American Cordilleras (see Fig. 9).

Mascons in the Oceanus Procellarum are patterned in a peculiar way. Under the Median Ridge, where the youngest basalts are developed, they appear on its both sides, thus indicating the deep lava filling zones. This proves once again that the mid-oceanic zone was not flooded by lavas during all the epochs of magmatism. The process of ocean filling occurred impulsively, as well as the floor of the Atlantic Ocean was overlapped by lava on Earth. The filling proceeded from margins towards the centre of the Oceanus. Thus, in its middle, there could be no old basaltic blankets under the young lavas.

The early impulses of magmatism in the centres of the Atlantic Ocean and lunar Oceanus Procellarum either did not develop at all or basalts underwent subsequent deformations. On Earth, early lava extrusions could be followed by the epochs of folding and then mountain formation. These assumptions stem from a pattern of fold zones on Earth. In the Oceanus Procellarum on the Moon the early magmatic impulses in the Median Ridge had developed, if at all, within the belt where arcuate ridges again appeared. In fact, this belt was conformed to the submerged rim of the gigantic Gargantua basin and at the same time to the zone of jointing the rims of smaller individual concentric bands. The middle zones of these bands on the two sides of the ridge are the very places where small areas were filled with thick lavas. It is under these lavas where mascons have been established.

The comparison of basaltic seas of the Earth and the Moon has made it possible to single out the Atlantic and Pacific types of filling the lunar oceanic and mare basins.

Atlantic-type basins on both bodies (Fig. 17)* have the following features:

- (1) the presence of median ridges with narrow rises and

* The scale in Figures 17 and 18 is chosen so that unequal basins of the Earth and the Moon could visually be compared (note that the Moon and the African continent have almost the same surface areas).

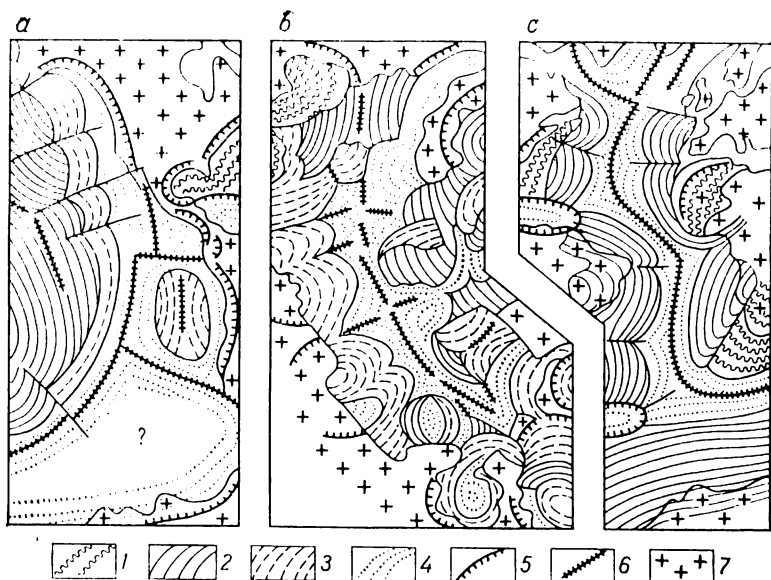


Fig. 17. Basaltic blankets in oceans of the Atlantic type:

a—eastern Pacific; *b*—Oceanus Procellarum; *c*—Atlantic Ocean. 1–4—basalts of different ages; 1—extrusion phase I (the Triassic and Jurassic on the Earth, about 3.8 thous. m.y. on the Moon); 2—phase II (the Cretaceous on the Earth, about 3.6 thous. m.y. on the Moon); 3—phase III (the Paleogene in the Pacific ocean), the Paleogene-Neogene in the Atlantic ocean, about 3.3 thous. m.y. on the Moon); 4—phase IV (the Neogene on the Earth, 3.0 thous. m.y. and later on the Moon) 5—terra and island arcuate mountains; 6—straightened ridges of converged arcuate mountains under ocean floor; 7—terrae and big islands

grabens; along their strike the ridges become continental mountains;

(2) the rejuvenation of lavas towards the median ridges as is traced by studying separate band- and crescent-shaped fields produced by pulsations;

(3) the absence of marginal mountain ranges on the coasts;

(4) the increase of radii of arcuate ridges from earlier through later epochs of the basaltic magmatism and the appearance of the belt of the youngest basalts on the two sides of the “straightened” common median ridge.

For Pacific-type basins on the Earth and Moon (Fig. 18), the following has been established:

(1) the absence of median ridges and appearance of peripheral mountain chains which on the ocean bed continue as island arcs;

(2) the rejuvenation of lavas towards the oceans’ periphery,

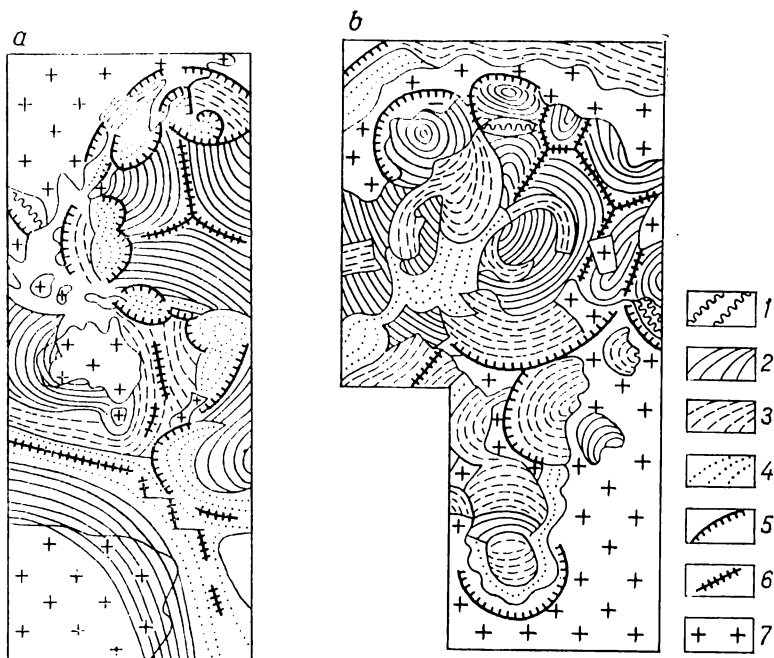


Fig. 18. Basaltic blankets in oceans of the Pacific type:

a—western part of the Pacific ocean; *b*—the Mare Imbrium. 1-7—basalts of different ages: 1—the global phase I of eruptions (the Triassic on the Earth, about 3.8 thous. m.y. on the Moon); 2—phase II (the Cretaceous on the Earth, about 3.6 thous. m.y. on the Moon); 3—phase III (the Paleogene on the Earth, about 3.3 thous. m.y. on the Moon); 4—phase IV (the Neogene on the Earth, about 3.0 thous. m.y. and later on the Moon); 5—terra and arcuate island mountains; 6—straightened ridges of converged arcuate mountains under ocean floor; 7—terrae and big islands

near-coast arcuate ridges, or towards island ridges separating young lava basins as traced by studying individual rounded, crescent-shaped or arcuate fields produced by pulsations;

(3) the shrinkage of volcanic regions from early through late epochs of the basaltic magmatism accompanied by separation of peripheral small concentric bands. These tiny volcanic maria are bordered by ranges in which older lavas of the floor are raised and deformed.

Figure 17 also shows that in the eastern Pacific Ocean both trends are recognized: lava rejuvenation towards the East Pacific Rise, and location of young lavas behind the continental mountains of the American coasts.

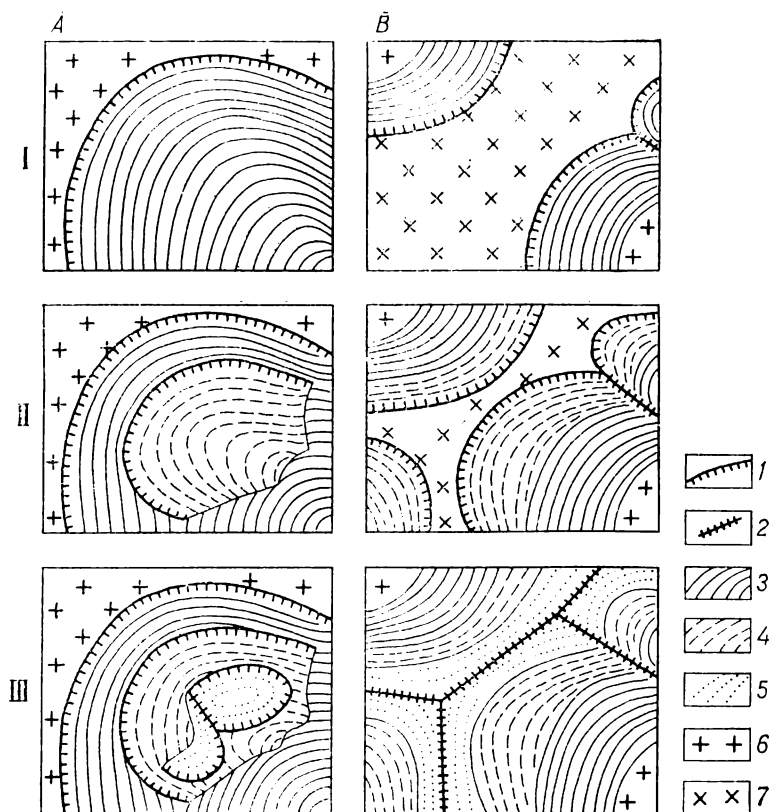


Fig. 19. Basaltic blankets of different ages behind the arcuate mountains on the Earth and the Moon:

A—basins of the Pacific type; *B*—basins of the Atlantic type. I, II, III—stages in decreasing the radii of the mountain arcs of different ages and formation of basaltic blankets.

1—mountain arcs; 2—straightened ridges from converged mountain arcs; 3-5—basaltic blankets behind the mountain arcs (3—eruption phase I, 4—phase II, 5—phase III); 6—terra, unknown terra substrate or that of an old ocean

The comparison of the terrestrial and lunar basaltic blankets in oceans makes it possible to suggest the following model of their formation.

The fixism, i.e. a constant position of the basement of the lunar terrae and oceans is obvious. A relative horizontal displacement is proved for rock complexes in the fold mountains of the Earth, but serious objections are raised as far

as the mobilism is concerned (i.e. the dislocation of blocks in their substrate). At the same time, similarly grouped structural elements take place in the basaltic floor of the oceans of these planets. These are the displaced or slightly thrust rock blocks within the arcuate rises, and their stable frames. They respond to the appearance of the thrust mountain arcs in different ways, while marginal troughs are formed on the frontal frames before the arc convexity; inside the arc concavity young basalts are issued on the rear frames.

When arcuate rises adjoin older ones from their inside (reduction of radii of successive arcs), all the basaltic blankets accompanying their appearance are located in the middle, i.e. inside the ring of differently aged ridges—cordilleras. The systems of mutually inserted mountain chains are formed (Pacific coasts). This is accompanied by a cyclic augmentation of the area of stable frontal frames. The mountain chains raised from the ocean as arcuate ridges gradually build up to form the marginal continental masses (Fig. 19).

In other cases arcuate rises, as if overstepping older ranges—cordilleras—and leaving them behind, advance upon the continent or ocean. Then the ancient ranges are covered by young final lavas (the growth of radii of successive arcs), and there occurs a cyclic expansion of the rear frames covered with basalts, i.e. a new ocean increases its area. The former lava-covered ranges immerse into the ocean (Atlantic coasts). The biggest arcs and small individual arcs adjoin along the common front, straightening each other. On both sides of the common straightened median ridge begins the extrusion of the ocean's youngest basaltic lavas having the same age. They are permanent features of the Atlantic-type oceans of the Earth and the Moon.

The Structures of the Earth and the Moon Are Symmetrical Relative to Their Axes of Rotation

The main land forms of the Earth show its asymmetry. The continents are mainly located in the northern hemisphere while the oceans in the southern. However, the central depression of the Pacific Ocean is in the same part of the eastern hemisphere where in the western there exists the most upraised continent of Africa. It is also possible to notice other features of similarity in positioning large structures

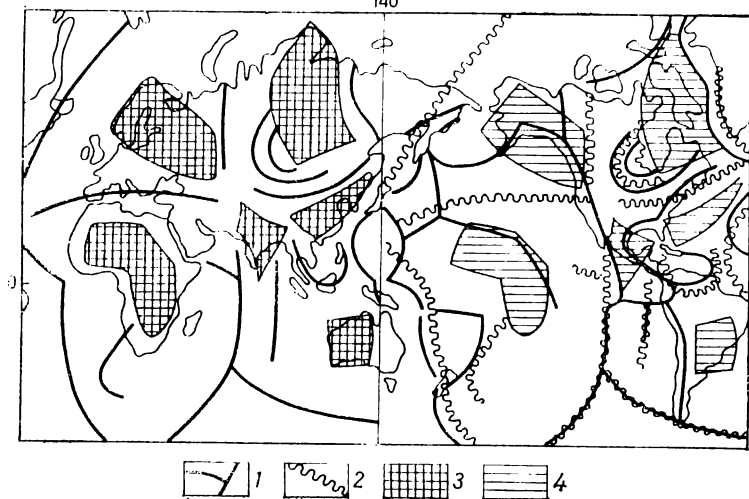


Fig. 20. Axial symmetry in distribution of the Earth's structures: 1—the axes of the Earth's active zones—main fold belts and mountain ranges; 2—the axes of active zones in the Western hemisphere, they are graphically copied in the Eastern hemisphere; 3—stable platforms in the Western hemisphere; 4—the same platforms, graphically copied in the Eastern hemisphere

of the western (Afro-Eurasian) and eastern (American-Pacific) hemispheres.

Figure 20 is based on the location of main mountain chains of the Earth and oceans as well as platform plains dividing them; some Precambrian structural zones are shown to indicate the boundaries of ancient platforms (see Figs. 2 and 13). The contours of old and young mountain chains separating the plain platforms of the western hemisphere are repeated in the eastern. As can be seen in Fig. 20, many large structural elements fully coincide while others are close and parallel. Besides, one can see that the outlines of active zones separated by stable blocks are symmetrical about the planet's axis of rotation.

Symmetrically placed structural elements are of different ages, therefore, the quality of the Earth's crust to be divided into more stable blocks and mobile belts is of a very ancient origin. The centres of stable blocks are cores of continental platforms. They did not drift across the planet's surface but were regularly encircled by successively younger fold zones, which adjoined the ancient blocks and extended the areas of flat undisturbed regions.

The Earth's development as a result of endogenic (subsurface) processes is doubtless. The natural axially symmetric positioning of the planet's large structures is not surprising. In different hemispheres there are similarly shaped elements which, however, are differently raised relative to sea level (highlands of Africa versus lowlands of the Central Pacific).

The similarity in the outlines of large structures in different hemispheres, i.e. their coincidence after a 180-degree rotation of the Earth, also demonstrates a regular axially symmetric disposition in the Earth's interior of energy sources that have determined the appearance of these structures.

The endogenic origin may also be assumed for the lunar structures. At present, the meteorite theory is the most popular in explaining the formation of its main basins. However, many geologists note that samples returned from the Moon contain much smaller amount of meteorite substance than could be expected (0.01%). And specific "impact" minerals that were thought to be a sign of the planet's bombardment by planetesimals can as well be formed by powerful endogenic explosions. Specific minerals produced under high pressure, such as stishovite, lechatelierite and coesite, can appear when many volatile components are concentrated above the magma chamber before the explosion.

In order to verify the concepts of a possible endogenic nature of lunar structures, it is very important to establish a regularity in their location. If impacts are surmised, one usually checks a possibility of structures—antipodes that should appear opposite to a place of the impact, i.e. on the axis passing across the planet's centre. Yet, no convincing indications as to the existence of the impact antipodes have been discovered.

At the same time, numerous efforts have long been undertaken to establish a regularity in the distribution of large impact craters. In 1976, the American scientists L. Jaff and I. Bulkley pointed out that old craters having evolved before the main basins are grouped regularly along the arcs what would contradict their impact nature.

The Soviet astronomers J.F. Rodionova and T.P. Sco-beleva established in 1980 that the largest structures of the Moon, Mars, and Mercury tend to concentrate in the same parts of the planetary bodies, this being in little agreement with incidental falls of meteorites which would have otherwise produced these structures.

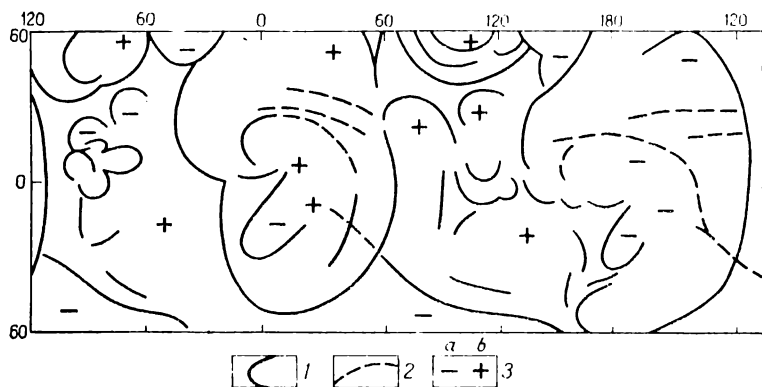


Fig. 21. The elements of symmetry of the Earth circular structures: 1—lineaments and structures established with certainty; 2—lineaments and structures established indistinctly; 3—a height relative to the average elevation of the surface (a—lowered areas, b—raised areas)

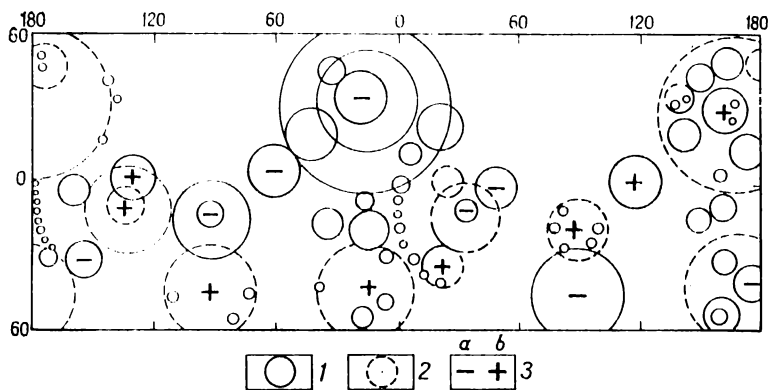


Fig. 22. The elements of symmetry of the Moon structures.
The key is given in Fig. 21

We can check the regularity in the distribution of lunar structures applying the same method used above for the Earth. The latter's axially symmetric pattern was formed by differently aged elements, hence for the Moon the age can also be ignored. This leaves only geometry of their distribution as an important consideration.

Figure 21 shows a schematic map of the Earth's arcuate lineaments for a region between 60°S and 60°N. Pluses or

minuses stand for similar intra-arcuate areas correspondingly raised or sunk in relation to an average level of the geoid's surface. In a schematic map of Fig. 22 the arcuate lineaments of the Moon with the same symbols for elevations and lows relative to a level of the selenoid are shown. "Complete Lunar Map" reveals that on the far side of this planet, at a site opposite to the Mare Imbrium, there is a swarm of large craters situated in the region of the highest lunar relief. An elevated terra with circularly-patterned craters is axially symmetric to the Mare Australe. Main circular maria of the Moon also have counterparts 180 longitudinal degrees away. The large cirques of similar radii or crater swarms arranged axisymmetrically in the other hemisphere (the distance is 180° longitude) are compiled with the main circular maria of the Moon. The circular lineaments also display a similar reciprocal grouping in different hemispheres (see Fig. 22). Therefore, the indications of the regular distribution of large circular structures on the Moon's surface are obvious.

So, the pattern of the largest structures both on the Moon and Earth is of a regular character. They lie in different hemispheres, symmetrically relative to the axes of planet rotation. Often, though not always, huge upraised regions of one hemisphere correspond to lows of the opposite hemisphere. The arcuate or ring ridges fringing or separating such areas are similarly positioned in the opposite hemispheres. Structural outlines of different hemispheres clearly coincide when shifted over 180 degrees in the longitudinal direction.

Since the inner, endogenic nature of the Earth's structures is undoubtful, it is plausible that during the formation of lunar mountains and maria the leading role was also played by subsurface activity of the planet.

Arcs and Rings of the Earth's Oldest Mountains

Ring and arcuate Precambrian structures of the Earth have long attracted attention of geologists. Their shapes and sizes were compared with circular mountains and basins on the Moon, and even a lunar stage of the Earth's development was suggested. Among scientists who popularized these problems, mention should be given to A.P. Pavlov, E.V. Pavlovskii, M.V. Glukhovskii, M.S. Markov, and S.V. Bogdanova. Ring Precambrian zones are usually classified ac-

cording to the existing geometric shapes of preserved, though strongly eroded, fold structures. For young fold zones of the Earth and structures of the Moon, the present author has shown a regular twin combination of arcuate mountains and adjacent basaltic blankets consisting of final lavas from each cycle of mountain formation. In analysing Precambrian material, this regularity permits one to easily reveal old concentric structures.

Precambrian fold concentric bands are of primary interest for the comparative planetology because their age is closer to that of lunar concentric basins. For instance, K. Schulz and P. Weiblen have drawn attention to a fact that the oldest part of the North American platform (the Superior Province) resembles in shape a lunar rounded mare formed about 3.8 thous. m.y. ago and filled with basalts that were later folded together with sediments accumulated on them (approx. 2.7-2.4 thous. m.y. ago). These scientists assume that old terrestrial basaltic 'mare' has a meteorite origin. However, geologists still believe that all Precambrian structures of the Earth had been formed by endogenic processes.

Beside the central Superior Province with its arcuately-arranged folds, there are two other areas on the North American platform with fold structures 2.4 thous. m.y. old. These are the concentric Wyoming Band in the west and the Slave Province in the northwest (Fig. 23).

Geologist K. Condie has studied the old units in Wyoming and showed a circular position of variously aged fold zones. The oldest folds here appeared 2.9 thous. m.y. ago. They were injected by granites, and older basalts (3.2 thous. m.y.) that remained in the centre of a fold rim are crumpled. After the rim had formed inside it the postfold basalts (the Stillwater Complex) issued again 2.74 thous. m.y. ago. They were crumpled together with the upper sedimentary cover, and a new concentric band appeared within the previously formed. Condie notes a centrifugal growth of temperatures and pressures in rocks making up this new concentric band. After its folding and flooding by new basaltic lavas (the Black Hills Mountains) these were subsequently folded. As a result, a nearly completely closed ring of structures appeared 1.8-1.75 thous. m.y. ago.

During this phase of folding and metamorphism the outer margins of the fold concentric band were penetrated by large masses of the earlier formed subsurface feldspathic

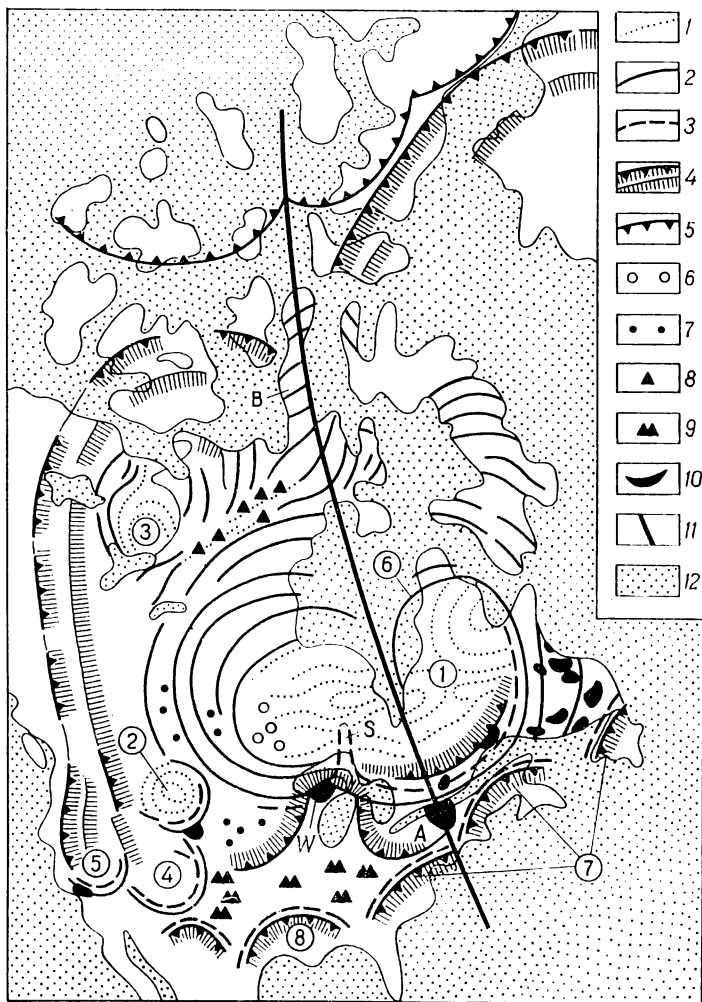


Fig. 23. The Precambrian concentric fold bands of the North American Platform:

1-4—ages of fold arcs: (1—about 2.5 thous. m.y., the Kenoran arc, 2—about 1.8 thous. m.y., the Hudsonian arc, 3—about 1.4 thous. m.y., the Elsonian arc, 4—about 1.0 thous. m.y., the Grenville and basaltic blankets behind the Grenville arcs); 5—Paleozoic fold arcs of Canada; 6-7—age of the fold basement under the sedimentary cover: 6—about 2.5 thous. m.y., 7—about 1.8 thous. m.y.; 8-10—volcanic belts and anorthositic plutons of different ages before the fold arc fronts: 8—about 1.8 thous. m.y., 9—about 1.4 thous. m.y., 10—anorthosites aged 1.4-1.1 thous. m.y.; 11—the through-structural lineament—a zone linking concentric bands of different ages; 12—water area. Concentric fold bands: 1—Superior; 2—Wyoming; 3—Slave; 4—the Front Range and the Southern Rocky Mountains; 5—Transverse Ranges; 6—Circum-Ungavian; 7—Pra-Appalachians; 8—Oklahoma, B—Butla Ridge, S—Sibley graben, A—Adirondak pluton, C—Wisconsin pluton

rocks—anorthosites (the Larami Range). The penetration occurred in that part of the ring on the south, where it adjoins two other arcuate fold structures. These are the eastern front arc of the Front Range of the Cordilleras linked with the arc of the Southern Rocky Mountains, and farther to the south, the arc which on coming to the Ocean becomes the Transverse Ranges of California (see Fig. 23). The folds of all these arcuate zones also formed 1.8-1.75 thous. m.y. ago. However, the process of folding in the concentric Wyoming Band was not yet completed. An additional successive phase of basaltic magmatism occurred in its centre; the basalts were overlain by sedimentary sequences and again became folded on its margin about 1.5 thous. m.y. ago (the Mazatzal Mountains). Finally, the folding was again followed 1.3 thous. m.y. ago by an impulse of basaltic volcanism in the middle of the concentric band.

Around the Superior Province there are two converged fold concentric bands crumpled 1.8-1.75 thous. m.y. ago (the Hudson epoch). The folds of this age extend in the east across the Labrador Peninsula and then turn to the centre of Hudson Bay (see Fig. 23). This gigantic oval structure is called Circum-Ungavian. Postfold basalts and large basite plutons issued behind this gigantic oval (Sudbury and others). The lavas, together with sediments which overlain them, were crumpled again along a more inner-sided arc approximately 1.5 thous. m.y. ago; behind these fold arcs still later issued basalts that were deformed 1.1 thous. m.y. ago, resulting in the youngest blanket of final basalts formed inside the late arcuate structures.

The entire area in front of this huge fold arc experienced an intensive warming up and penetration of anorthosites during folding that occurred between 1.4 and 1.1 thous. m.y. ago. Anorthosite masses of this age (possibly, the older ones as well) are widely distributed on the Labrador Peninsula and to the southwest of it. This region during the intrusion of anorthosite plutons was also in front of other, more southern arcuate fold zones, convexing northward, i.e. in the Pra-Appalachian arcs. The folds of the Green and Blue Mountains of Newfoundland situated in the region of the Pra-Appalachian were also formed about 1.5 thous. m.y. ago and were similarly accompanied with basaltic extrusions from behind. A consecutive phase of folding again developed here between 1.3 and 1.1 thous. m.y. ago.

A powerfully warmed-up band with regional distribution of anorthosites between the fronts of fold arcs reversed to each other extends to Great Lakes in the centre of the continent. Geosynclinal troughs and fold zones developed both on the north and south of the band during the so-called Grenville geotectonic epoch. Adirondak, the biggest pluton of anorthosites, lies in the zone of linking the Pra-Appalachian southern arcs. Another gigantic Wisconsin pluton, an anorthosite massif, is situated to the south of Lake Superior, in the area where northern concentric bands merge. The zone of linking the northern concentric bands is complicated by a narrow subsided depression of the Sibley graben. Younger fold arcs of Grenville age (1.4 thous. m.y.) are curved farther south, on both sides of the Wisconsin massif. Behind them there are basaltic blankets drilled by boreholes beneath a sedimentary cover. Crescent shaped basaltic blankets link in the area of Lake Superior where, through the Keweenaw graben, they merge into the gigantic basite Duluth pluton.

Coarse-clastic conglomerates are found beneath the platform cover of intermediate and acidic lavas in the Central United States, on the continuation of the band of anorthosite plutons. This area is also located before the frontal zones of several fold arcs. These are northern and southern arcs of the Pra-Appalachians as well as a fold arc in Oklahoma (the Arbuckle upland) with granites 1.4 thous. m.y. old and basalts behind the arcs (the Llano upland). Being surrounded by fold arcs, this area underwent an extensive warming up. Heat waves emanating from each concentric band propagated outward from a centre. Volcanic belts appeared here 1.4-1.1 thous. m.y. ago, when the surrounding concentric bands became folded. Earlier the same type of area was represented by the eastern zone of anorthosites (it is called the zone of "Elsonian-Grenville rejuvenation". Volcanic series on Earth were washed out owing to a lasting uplifting. Only anorthosite and metamorphic "roots" of the former volcanic belt remained preserved.

Also known is an old (1.75 thous. m.y.) volcanic belt near Athabasca Lake in the northwestern continent, where older fold concentric bands link each other. It appeared during the epoch of their development, approximately 1.8 thous. m.y. ago.

A zone of the Grenville epoch of folding (1.1 thous. m.y.),

the gigantic semicircle around the entire western part of the platform, extends along the Cordillera, Canadian Archipelago margin, and farther to Greenland. Everywhere behind this arc, in the Belt, Grand Canyon, and Coppermine units, and in the Thule unit of Greenland a band of basaltic lavas is traced. In the north the fold system becomes two semi-ovals separated by a "spur" of the Butia Ridge, its continuation to the south being the zone where central Hudsonian fold ovals link. Still farther to the south there are the Adirondak bulge and the zone of linking the Pra-Appalachian arcs. On continuing this line to the north of the Butia Ridge, we can notice linking of younger Paleozoic fold arcs of the Canadian Archipelago (see Fig. 23). The zones of linking the fold concentric bands are often accompanied by increased mobility producing horsts or grabens long after the concentric bands has "died". At the same time, it is probably a very deep-seated inhomogeneity of the Earth's interior that makes fold arcs of different ages link along certain lineaments.

Thus, in the USA territory there are several fold concentric bands whose margins were successively (in fact simultaneously) subjected to the phases of crumpling. During their termination, on the surface inside the bands basaltic lavas finally issued. Sediments covered the lavas in troughs, and subsequent epochs of crumpling again brought about their deformation resulting in "follow-up" arcs. In case the fronts of adjoining concentric bands merged, the crumpling gave way to anorthosite magmas, which intruded into the zone of linking. A fold arc thus created was penetrated by granites and only after that younger basaltic blankets formed inside the arcs.

Several concentric bands of different ages are singled out on the Baltic Shield. Basaltic blankets are located inside their fold rims injected by granites (Fig. 24). In the middle of the shield there is a gigantic ring with its centre in Finland. In the direction of the Kola Peninsula the ring faces the convex fronts of two smaller fold arcs. The third small arc is indicated in the extreme northwest of the shield. Finally, there is one more fold ring in the southmost part of Scandinavia.

All arcuate fold zones were deformed within the interval of 2.1-1.9 thous. m.y. In the folds there are old basalts (the so-called Lopii series and their equivalents). Before the

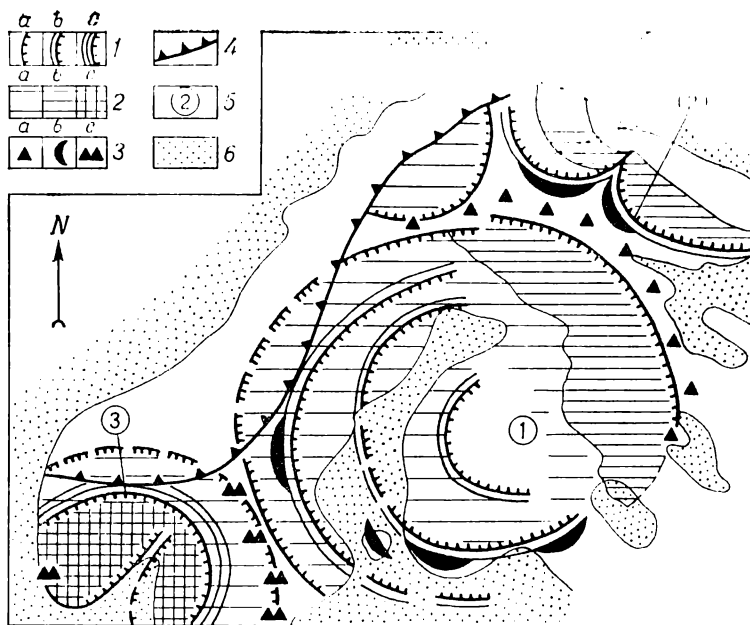


Fig. 24. Precambrian concentric fold bands of the Baltic Shield: 1—fold arcs of different ages (a—about 2 thous. m.y., b—about 1.7 thous. m.y., c—about 1.1 thous. m.y.); 2—basaltic blankets of different ages behind the arcs (a—about 2.0 thous. m.y., b—about 1.7 thous. m.y. and older, c—about 1.1 thous. m.y. and older); 3—volcanic belts and anorthosite plutons of different ages before the fold arc front (a—about 2.0 thous. m.y., b—about 1.7 thous. m.y., c—about 1.1 thous. m.y.); 4—a line of thrusting of Paleozoic rocks; 5—concentric fold bands (1—Finland, 2—the Kola Peninsular, 3—Southern Scandinavia); 6—water area

fronts, in the zones where all the fold ovals link each other during the deformation volcanic masses of different composition and coarse-clastic molasses were formed. These rocks of the "volcanic belt" (1.2-1.9 thous. m.y.) are most complete in Karelia north of Lake Onega. They are named the Suomii and Soriolii Formations. Behind all the rims injected by granites final basalts issued immediately after the folding, which had produced these rims. Generally, the extrusions took place simultaneously (1.9-1.8 thous. m.y. ago) over huge areas. It is only in Karelia that the basalts have preserved their platform flat-lying occurrence (the Yatulii Formation). Behind the Kola fold arcs (Pechenga, Imandra-Varzuga) and inside the ring of folds of South Scandinavia, as well as in the southwestern half of the Median Finland

concentric band, basalts of the same age (equivalents of the Yatulii series), together with their sedimentary overburden, again folded 1.8-1.7 thous. m.y. ago, and thrusting towards the outer side of the arcs occurred.

That was an epoch of deformations, which is called Svecofennian. In front of the revived fold arcs of the Kola Peninsula large anorthosite masses of this age (Kandalaksha, Kolvits layers) appeared at the base of the shovelled slabs. They have been described by E. Sharkov in detail. Huge anorthosite plutons with specific coarse-grained rapakivi granites also appeared in front of fold arcs in the Western Finland concentric band. These are Vyborg, Salmin, Riga plutons described by O. Bogatikov. Similar plutons occur also on the western coast of the Baltic Sea. Emplacements were accompanied and a little bit later followed by accumulation in the volcanic belt of thick piles of intermediate and acidic lavas and conglomerates of the Subjötner member. The accumulation occurred on the surface in front of the arcs.

The Svecofennian folding was a final one inside all the northern fold arcs. By the end of the epoch of folding, basites of the Vepsii Formation again intruded 1.65 thous. m.y. ago in the eastern half of the Finland ring, over the same area where older lavas were still flat-lying. In its western part, pluton equivalents and lavas of this age, together with their sedimentary overburden, make up fold complexes.

The folding of 1.65 thous. m.y. ago developed also along the margin of the South-Scandinavian concentric band. Final basalts (within the Sel'ur and Capebo series) issued behind the folds. The following phase of folding occurred 1.5 thous. m.y. ago (the Gothic epoch) and deformed the series containing basalts. Plutons of anorthosites and rapakivi intruded in front of the folds shovelled towards the outer side of the arc. A volcanic belt with acidic lavas and conglomerates (the Subjötner member) formed between the Finland and South-Scandinavian concentric bands. The development of the belt was completed 1.2-1.0 thous. m.y. ago as did the South-Scandinavian concentric band breaking down into two small ovals whose folding took place 1.0 thous. m.y. ago. They converge in the middle of the concentric band and are injected by granites. Later on the Oslo graben appeared here. In the centre of the small ovals final basites of this age are emplaced in the slightly disturbed layers, similar to those widely developed to the north (the

Jötner Formation). At this time the entire western and north-western margins of the East-European platform was located behind a gigantic Galician fold arc, which underwent folding toward 1.0 thous. m.y. ago when the basites intruded everywhere.

So, Precambrian fold concentric bands of multistage development are known to occur on different continents. Before their converged fronts, volcanic belts with acidic magmatism appear and anorthosite masses intrude at depth. These replace younger marginal troughs and appear in the areas that have not yet attained the rigidity of platforms. It was only in the preceding cycles that such zones, situated in front of folds, underwent crumpling. Inside fold arcs and along their concavity final basalts issuing in successive cycles were in a number of cases again folded by the next phase.

The rear and frontal sides of Precambrian fold zones are detected correspondingly by the folds of marginal volcanic belts and anorthosite plutons, and the folds of mantling basalts or intrusive basites of a certain age. This helps to make obvious the general form of the zones in plan. In this case arcuate and circular configurations of the fold zones are determined rather convincingly.

Arcs and concentric bands are frequently of multiphase development. They have different dimensions and coeval development. The concentric bands of the Wyoming, Circum-Ungava, and Finland types, their diameters being 200-500 km, are comparable to regular circular maria of the Moon. Large and gigantic semicircles and arc-type ovals surrounding the North American continent on the west, with their diameters reaching 1 000 km, can be compared to the huge Imbrium and Australe maria. Finally, small concentric bands of the South-Scandinavian type (200 km in diameter) are similar to small maria and large craters of the Moon.

The above approach of recognizing the rear and frontal parts of arcuate and circular fold zones of the Precambrian has been used to present in a new light a spatial position of the specific areas characterized by extremely powerful warming up and intrusion of the anorthosite-type plutons. These areas are usually called "the zones of metamorphic rejuvenation" implying that their old units change, though folding as such is lacking. Their fold substrate undergoes recurrent metamorphism. Such zones are characteristic of the areas similar to the Grenville Block or the southern margin

of the Baltic Shield. In addition, there is an opportunity to make more exact also the time and place of "anorthosite belts" initiation. The Belgian geologist P. Mischeu has long ago attributed appearance to the influence of adjacent zones of folding.

The following is a general succession of the events for each tectono-magmatic stage producing fold mountains:

(1) early magmatic manifestations—anorthosites before the front of a "living" geosyncline that has already got a young basaltic blanket;

(2) subsequent magmatic manifestations—granites intruding against a background of folding and metamorphism in rising mountains;

(3) late magmatic manifestations—final basalts behind the risen fold mountains.

A link of anorthosite magmatic intrusions should be included into the known stages of magmatism of a single geotectonic cycle identified by H. Stille and Yu. Bilibin. Now we can draw a parallel with the stages of planetary crust formation on the Moon: the earliest magmatic manifestations—anorthosites of lunar terrae; the subsequent ones—CREEP basalts of lunar ringed mountains and their feet (homologues of the Earth's granite magmas); and late magmatic manifestations—basalts of lunar maria behind mountains, inside anorthosite rims.

Early geosynclinal basalts seemingly disappear in this succession of magmatic manifestations of a single stage (cycle). However, the final lava extrusion is the same as the initial one, they are like the two sides of a coin. The basalts that conclude one of the cycles "open up" the next cycle, if it is developed at the same place. Final basalts of the completed cycle of mountain formation should be put at the very beginning of a new cycle. However, an a priori assumption that the phase of basaltic eruptions occurs at the "start of a circle" (spiral) involves greater responsibility than leaving it at the end, because a beginning of the earliest cycle, which caused the formation of fold geosynclinal mountains on Earth, is unknown. At the same time widely known are final basalts with their preserved flat initial occurrence. They were not involved in later folding.

The outlines of Precambrian fold megastructures, as revealed on the basis of the approach determining their rear and front, puts on the agenda the question of dynamics of the forces giving rise to fold concentric bands and arcs.

Earth megastructures of the central type expressed on the surface by circles, arcs and rings now attract great attention. They have been revealed during the past years on the basis of the remote-sensing survey of the Earth's surface, comprising the interpretation of space photographs, as concentrically oriented relief forms and different geographic objects. They are mostly shown only by arcuate and circular disturbances in the Earth's surface continuity as well as by chains of magmatic bodies or zones of strongly changed crushed rocks.

Such structures are characterized by rounded shapes in plan and also radial-concentric arrangement of their different elements. Such elements may be pronounced differently, and being well represented in one part of a concentric band, they may be absent in the other. In the three-dimensional space, the structures of the central type possess the symmetry of a cone.

V. Solov'ev interprets such symmetry type of the objects as being due to the very nature of the planet's constitution. He cites a statement of the well-known crystallographer I. Shafrafovskii to the effect that "...the gravitational field of the Earth in any point of its surface is characterized by the symmetry of a cone".

The downward tapering of complex plutons of alkaline and basic magmatic rocks, as well as the downward convergence of kimberlite explosion pipes forming thin veins, exemplify the objects with a small surface radius possessing a clearly expressed cone symmetry. Volcanic structures are typical representatives of small bodies with conical symmetry and small diameters (the first few kilometers on surface).

The relationships between the largest cone-like objects and the fold zones of different ages show that arcuate fold zones created by the geosynclinal process on Earth are accompanied by intra-arc basaltic blankets similar to lunar volcanic maria. The margins of many megaconcentric bands virtually coincide with epigeosynclinal fold arcs of the Earth. Among a multitude of such structures one can single out Central Kazakhstan, the Carpathians, Verkhoysanskii Khrebet and Novaya Zemlya. Clearly expressed are the huge, reciprocally conformal, planetary-scale arcs of the Mongolia-Okhotsk geosynclinal belt.

Precambrian initiation of many fold concentric bands has

been convincingly proved by geologic evidence. Differing intensity of their development and crumpling of the appearing arcuate folds indicates that the life of the structures was undoubtedly determined by the Earth's inner energy. Some segments of individual arcs and rims actively developed in some cycles and stabilized in others. As a curvature of radius of each consecutive fold arc could increase from one geotectonic cycle to another, the former folds were found inside. If the curvature was shortened, the consecutive fold arc appeared to be "enclosed" into the former one. Predominant overturning and overthrusting of folds, i.e. their pushing out always occurred towards the convex, outer side of the arcuate chain of mountains. A direction of thrusting is indistinct where the outer margins of contiguous arcs join to contact each other, and the areas between them or under their converged fronts undergo the greatest warming up, secondary changes, intrusion of intermediate and acidic magmas.

Old fold arcs and their supposed continuations along the ring are renewed repeatedly to a different extent. They appear to be visible under the younger concentric forms. Therefore, the fold systems of different ages present a mixed general pattern. However, the multiple revival of arcuate ranges of different sizes with progressively occurring juxtaposition of their peculiar deep-seated features has formed a patchy and banded pattern of the modern distribution of crustal thickness on Earth. The distribution is roughly that of plain platforms surrounded and separated by mountain fold belts. At the same time, inside almost uniform platforms geophysicists sometimes reveal circular and crescent-shaped zones of the Earth's interior with specific physical parameters, these being the traces of former, more distinct differences.

Precambrian fold arcs and rings and younger fold-geosynclinal arcs developed in a similar way. Intra-arc blankets of final basalts appearing at the end of a stage of mountain formation again sank along a new ring-trench. In front of the trench convexity, compensation marginal troughs were formed on old blocks, and where folding had just occurred, feldspathic magmas ascended from depths to form anorthosite plutons or surface marginal volcanic belts. The arcuate trench was gradually filled with sediments subjected to a new folding and intrusion of granite magmas. These warmed-up and crumpled complexes of geosynclinal troughs then rose

up, shifting towards their outer side and forming the ridges of a new generation. Along the same side of the fold the mantling basalts again flowed out forming the seas. The youngest basaltic sea of the Earth is situated inside the fold ridges of the modern land sea.

The geologist Yu. Zaitsev has shown with reference to Kazakhstan that concentrically zonal development of fold zones is characteristic also of the Paleozoic era in general. The concentrically zonal constitution of the Mesozoic and Cenozoic fold mountain systems having appeared from geosynclines was studied in detail as far back as in the thirties of this century by the well-known Dutch geologist H. Van Bemmelen. Young fold arcs of the Melanesian island chain and Western Pacific are clearly expressed even on geographic maps.

Centrifugally increasing metamorphism and strain are accompanied by fold thrusting towards the outer side of the arcs indicates that the dynamics of fold concentric bands development is that of a stress wave propagating centrifugally from a point above the subsurface source. The source provides fluids, heat and changes the rocks accumulated on the surface. However, all transformations do not occur above the subsurface source. Folding, warming up and magma intrusion occur in zones with the maximum thickness of rocks along the concentric systems of arcs extending away from the source. The concept of "the dynamics of the centrifugal wave" in the development of the Earth's geosyncline should be added to the existing ideas of the statics—the rear and front of a fold zone.

The Centrifugal Wave in the Development of Mountain Arcs

Mountain arcs of the Moon are similar to fold mountains of the terrestrial continents, and mare ridges and phantoms to oceanic ridges of the Earth's oceans. Continental and oceanic chains of rises often continue each other both on the Earth and on the Moon. It can be assumed that oceanic ridges on our planet are lava-covered continuations of continental mountains.

A combination of basaltic blankets and their bounding of mountain ranges are present on both planets. Basalts always appear on a concave side of arcuate fold uplands

after their formation. The extrusions of basalts on Earth correspond to the final magmatism of geotectonic cycles creating mountains.

The terrestrial structures of arcuate uplands are overturned and thrust always toward the outer side of the arcs. On the convex side of fold arcs, in front of thrusts, there are marginal troughs of old platforms or marginal volcanic belts.

The continental trap blankets continue in oceans as floor lavas of the same age. Taken together, continental-oceanic basaltic fields form ovals, semi-ovals, or huge arcuate belts bounded along the convex front by a common chain of mountains standing up on land or submerged in oceans.

The Earth's fold arcs of very big radii seem straight on maps. This, in particular, led to an idea to the effect that the crust of our planet has developed in a special way. The linear tectonics is explained in terms of modern mobilism, or tectonics of lithospheric plates. The basaltic floor in oceans is assumed to outgrow and move as a result of subcrustal flows. The above plates are then assumed to be shoved down into the mantle in front of continental margins. It is a subduction giving rise to mountains. This is how mobilism explains unidirectional overturning of folds inside global linear mountain belts.

However, there are also smaller fold arcs on Earth suggesting a great number of "plates", which are moving, sinking and rotating in the most complicated fashion, sometimes simultaneously and in all possible directions. Different explanation for folding in the arcs of a small radius is provided by diapir rising with centrifugal gravitational "creeping" of the rock slabs. Paleogeographic reconstructions, however, usually do not confirm a major uplift behind the fold arcs during the epochs of thrust formation.

Horizontal movements of layers in fold zones of the Earth are reliably substantiated; they develop over tens of kilometers (according to drilling results). At the same time, "transparency" of old basement faults under thrust layers is not consistent with the large shift of crustal blocks of the basement. The regularity in the distribution of continental-oceanic fold-block mountain belts that is symmetric to the axis of the planet's rotation contradicts the grandiose movements of the entire continents.

Centrifugal ejection or removal of the filling or inclined

and bulged-up substance of terrae to peripheral circular highlands has been identified on the Moon. Also obvious is the fixism of the basement of terrae and oceans. Parallel to this, when basaltic floor in oceans of both planets is formed, similarly grouped common structural elements appear. These are shifted or slightly outward-thrust rocks of arcuate highlands and their stable frames that differently respond to the appearance of raised mountains. In front of the arc convexity, on the frontal frames, marginal depressions appear, and inside the concavity, behind the frames, young basalts issue.

The author suggests that the concept of the Earth's geosynclinal process be enriched with a genetic principle of ringed structure formation that is common for planets. The principle explains the similarity in morphology and stage formation of the corresponding structural pairs on planets—arcuate mountains and basaltic blankets behind them. It should also account for immobility of the planet's crust substrate and horizontal displacement of the substance of the arcuate fold mountains. This new principle is a tectonic effect of the centrifugal wave in geosyncline development (it is outlined below as a hypothesis).

Let us assume the supremacy, pre-eminence of a horizontal basic wave during the geosyncline development. The wave propagates in near-surface spheres of the Earth away from an epicentre located above the deep-seated source. Drawing an analogy with the source of an earthquake, G. Gorshkov attaches a name deep-seated source to the substance (mantle) having previously accumulated a potential energy. An idea of the geosynclinal wave renders more concretely the position of stable frames in front or behind thrusts of the fold zone. In a mechanical sense the geosynclinal wave (vector) can be compared to a basic wave originating in the planet substrate during an impact, which for the basic wave may in principle be external, meteorite one as well.

The centrifugal horizontal wave is produced by a pulsation of subsurface energy determining the vertical shock—explosion. The propagating near-surface basic wave either gradually dissipates in a cold lithosphere or is slowed by a pliant zone of a low-density substance. It is the asthenospheric zone under the blanket of young hot basalts (Fig. 25a, b). In the latter case a wave of relief appears.

An area of the relatively thinned density of the mantle

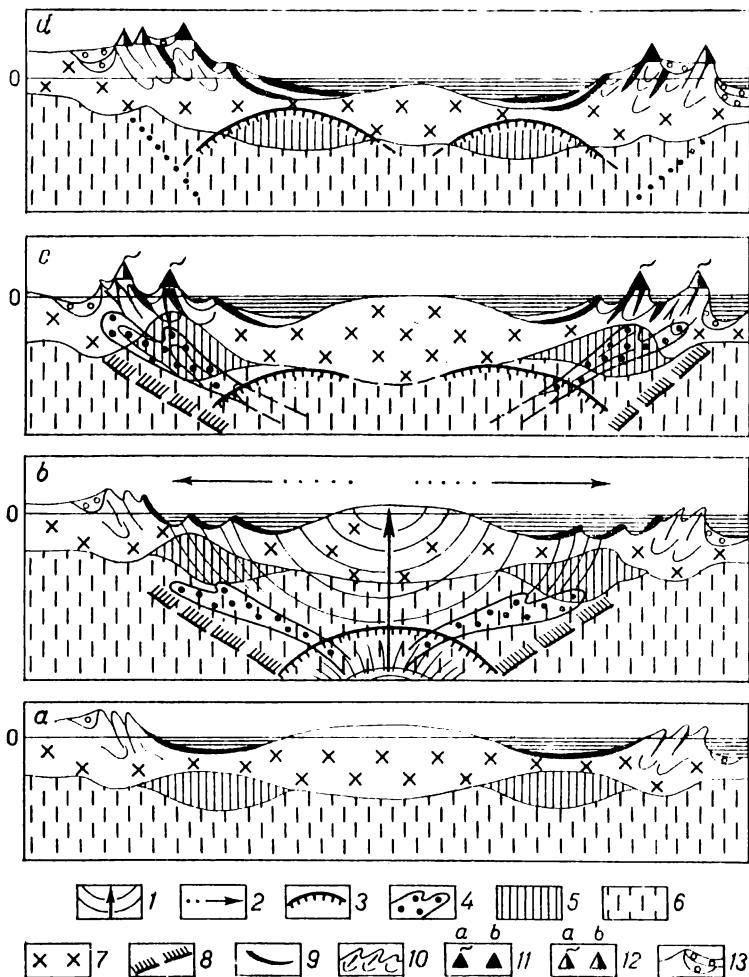


Fig. 25. A schematic development of geosyncline according to the principle of the centrifugal wave:

a—fold zones and rear basaltic maria of the first cycle; *b*—appearance of a new second-cycle geosyncline; *c*—development of the second-cycle geosyncline (active island arcs, volcanic belts in frontal fold zones); *d*—folding, granitoids, orogenesis and final magmatism of the second cycle. 1—the action of a deep-seated shock-explosion and base waves stemming from the epicentre; 2—a vector of the centrifugal wave; 3—conductive heat front; 4—convective flows of heat and gases; 5—asthenosphere; 6—mantle; 7—lithosphere; 8—seismofocal zone; 9—basalts; 10—fold structures; 11—geosyncline volcanoes (*a*—active, *b*—extinct); 12—volcanoes of marginal volcanic belts (*a*—active, *b*—extinct); 13—marginal foredeeps of different cycles

substance is produced and left behind by the centrifugal wave of compressive stresses. The subsurface flow of heat and fluids from the explosion is driven by the wave towards the zone of its maximum retardation, where the asthenosphere again pinches out under a margin of the blanket of young basalts. This leads to the formation of a zone of mantle density inhomogeneity inclining in the direction from the frontal stable frame toward the centre of the endogenic explosion. A corridor of convective heat and mass transfer (seismofocal zone) forms above the zone and on the Earth's surface an upland or a system of uplands separated by troughs appear along the front of the centrifugal wave.

A similar explanation for seismofocal zones that taper like a funnel towards the subsurface source was introduced by G. Azhgirei. He emphasized that only the hanging wing of seismofocal zones could be a place where granites are formed.

A "living" geosyncline is a wrinkle or a system of parallel crustal wrinkles, i.e. trenches and island chains. A new addition to the concept of their development is that an arcuate wrinkle could migrate in space with time. Its earlier sedimentary and volcanic fillings can be squeezed and splashed out, "rolling" over later ones. They are driven by the wave creating landforms (Fig. 25c). Like a tsunami wave, it is the highest near its "coast", i.e. in the zone characterized by a sharp thinning of the asthenosphere near a frontal stable frame. It is here that a fold upland (orogen) appears (Fig. 25d). The stable frame may be continental or oceanic, with old floor basalts. Owing to heat conductivity of the medium, the delayed conductive thermal front slowly rises up from the subsurface source. Behind arcuate mountains the front reaches the thinning out mantle substance, from which basalts are melted out. The lavas flowing out on the surface are final in the cycle of mountain formation.

According to the proposed approach, only the systems of deep-water depressions and adjacent rises on the ocean floor covered by the youngest Neogene basalts might be regarded as a modern geosyncline. These are the so-called "behind-arc" structures of the Western Pacific margins. It is only under young lavas that there is an asthenosphere lens capable of "catching" and slowing a new wave of stresses produced by any subsequent endogenic shock—explosion.

The proposed hypothesis of "the centrifugal wave" is capable of fitting together the well-known geologic and geophys-

ical data on island fold arcs in ocean, volcanic belts, deep-water trenches and seismofocal zones, in complete agreement with the classical theory of a geosyncline. The geosynclinal theory, however, does not provide clues as to the shape of an active area in plan or the place of its appearance. The proposed hypothesis, however, specifies the place of a new geosyncline by using the concepts of rear and front for any profile across the fold arc or a set of fold arcs. It is unnecessary to have the concepts of horizontal movements of large lithospheric blocks as the means for explaining monovergent geosynclinal fold mountain systems, i.e. those asymmetrically overthrust towards one side.

So, it can be established that in each geotectonic stage, corresponding to an impulse of internal energy of the planet, occurs a regionally expressed spatial differentiation of its upper cover producing granite arcs with anorthosites along their fronts and basaltic patches inside.

Those areas of the primary shell that got between frontal arcs of several endogenic concentric bands became particularly saturated with subsurface anorthosite melts, and they are fringed by ranges composed of deformed and granitized rocks. Basaltic depressions remain behind the barrier of mountain arcs. Intercircular areas can be thought of as being embryonic cores of sialic continents.

Subsequent development of these or similar concentric bands results in expansion of the core with a granite fringe and its new consolidation (cratonization). These transformations are effected by heat and fluid flows making frontal volcanic belts of intermediate and acidic rocks. The belts have anorthosite and metamorphic roots. On the opposite, behind-arc basaltic maria will be recurrently flooded with lavas during the subsequent cycles. This should occur at the end of each stage when another consecutive mountain arc attaches itself to the outgrowing sialic core, being the embryo of the continent.

Thus, the principle of the centrifugal wave in the development of mountain arcs of the Earth can account for the appearance, on the one hand, of initial cores of concentrated aluminosilicate feldspathic substance (sial), and on the other, of areas with predominating basalts and relative depletion in sialic substance of the below-basalt near-surface planet's shell. The process of cyclic spatial separation of the primary substance of the planet is not strictly single-oriented. Sub-

surface sources of endogenic explosions appear at different times and in various places. The law governing their activation and the place of development is unknown.

When studying crustal history of the Earth one should consider the time variation of predominant magma products. So, among the Earth's oldest deposits (4-2.5 thous. m.y.) mainly developed are anorthosites and related with them grey "gneisses" of indistinct genesis. Primitive (low-silica) basalts are in subordinate amounts and granites are practically absent.

Since about 2.5 thous. m.y. ago crustal granitization became active and old sediments having differentiated on the surface by hydrosphere and atmosphere began to undergo transformation during the development of mountain arcs. At this time mountain rings with internal basaltic patches also appeared. Such concentric rings are the traces of centrifugal waves differentiating the near-surface planetary substance. According to the author of this book these were shocks from endogenic energy explosions. Global appearance of granites on Earth 2.5 thous. m.y. ago could also be a result of an exceptionally effective phase of accumulating volatiles under the "pillows" of sialic continental blocks having sufficiently evolved by that time.

Later on a long period of time in Earth history (from 2.5 thous. m.y. to 0.25 thous. m.y.) was marked by extensive development of granites inside fold mountain arcs and, partially, in front of them. Subsurface heat and fluid flows would actively alter surface sediments piled up in geosynclinal troughs. By the end of this stage basaltic blankets behind mountain arcs would begin to group gradually into vast uniform areas almost completely flooded with lavas covering the substrate partially processed by mafic intrusions. Now thick sedimentary lenses would accumulate solely on the margins of sialic blocks. The processes of granitization could only occur here if activated concentric bands, conductors of endogenic energy, are present. A role of granites in endogenic single-cycle triads proves to be geographically limited. They develop on the activated continental margins.

During the past 0.25 thous. m.y. of the Earth history endogenic energy impulses were represented and expressed mainly by final basalts. Now their blankets along the front are often bounded only by arcuate island rises composed of older deformed basalts inside vast oceans.

The homologues of granites on the Moon, i.e. KREEP basalts, prove to be younger (3.9 thous. m.y.) than anorthosites and representatives of "pre-basin" basalts. According to clastics in continental breccias, basalts are more than 4 thous. m.y. old. KREEP basalts, that are younger than lavas in mare fillings, have not been yet discovered.

It can be supposed that areal differentiation of the primary substance caused by endogenic explosions and effected by centrifugal waves had already predominated at the early pre-basin stage of the lunar crust development. However, the separation had been involving only large rims composed of anorthosites and small, inner basaltic patches. After the crustal segments had been consolidated to a certain extent, a critical stage of the most powerful explosions began. It was these explosive acts that formed main lunar basins surrounded by circular ranges. The KREEP ejecta substance mostly enriched with volatile components settled down at the feet of the ranges. These events, occurring within short time (100 thous. m.y.), probably were too energy-consuming. Therefore, all subsequent stages of impulsive energy discharge from the Moon's interior were mainly expressed by basaltic extrusions during one more thousand million years. Lavas filled the later depressions bounded by low arcs of mare ridges.

Centrifugal waves determining, in the author's opinion, the development and shape of differently curved arcuate fold zones of the Earth are undoubtedly produced by its endogenic energy. A conventional viewpoint is that the appearance of multicircular structures is caused by the energy of asteroid impacts.

However, the comparison between all solid planets and the Earth convincingly favour another alternative, one explaining their main structures by intraplanetary energy.

The Moon Is a Simplified Model of the Earth

The study of volcanic blankets of the Earth's external basaltic shell and the latest research on the volcanic filling of "mare" depressions on the Moon have shown that in seas

and oceans of both planets there are large separate fields (isometric patches or bands) of lava blankets mantled on each other. Each basaltic field was formed during one of the epochs of regional volcanic extrusions.

Basaltic blankets on the planets appear *simultaneously* in different widely separated areas. Basaltic fields formed during any epoch of volcanism are similarly built. Magma from the planetary interior was also similarly delivered to the surface through a complex system of fractures. This indicates *global* impulses both on the Earth and the Moon.

These were outbursts of volcanic eruptions caused by repetitive warming up of planetary subsurface zones. Any of the volcanic impulses is more or less distinct in some regions and it may not be at all displayed in others. Before each consecutive impulse, i.e. a global outburst of eruptions, producing individual lava fields, in a particular area of the planet an arcuate or ringed rise appears. It borders the resulting depression in which basalts issue later.

There are two types of boundaries of separate basaltic fields, either old ones on the Moon formed 3.8-2.5 thous. m.y. ago, or young ones on the Earth (including only those formed over the past 240 m.y.). *Convex* boundaries are usually represented by an arched rise—rim. The rim can lie entirely on a continent or in an ocean, or it can continue from the continent to the ocean floor. *Concave* margins of arcuate belts or crescent-shaped basaltic blankets are formed by the bulging of continental basement of the substrate or the exposure of older basalts on the ocean bed.

Bordering elevations of the relief are absent here, a basaltic blanket becomes thin and pinches out.

The Earth's arcuate mountains near basaltic fields are represented on continents by geosynclinal fold zones. Each geotectonic stage producing fold mountains was terminated by basaltic extrusions. Basalts are always final manifestations of the interior activation at any stage (cycle) of downwarping, accumulation of rocks, their folding and subsequent uplifting. Besides, basaltic blankets are formations behind fold mountains, as lavas always issue to the inner side of mountain chains with different curvatures.

In the terrestrial oceans mountain rims of young lava

basins are often represented by island arcs. Their fold basement contains crumpled layers of old rocks and basaltic lavas thrust towards the outer side of the arcs.

The rims of basaltic maria on the Moon are arcuate or ringed cordilleras. Inside their ring the basaltic blanket often does not mantle the entire area, and then it is a crescent or a semicircle in plan. The cordilleras are made up of the bulged-up continental base blocks centrifugally thrust towards the outer side. They may be also composed of deposited breccias ejected away from the rim concavity. Curved rises bordering frontal parts of basaltic fields in lunar oceans are represented by low ridges where older basaltic lavas are raised and deformed with noticeable thrusting of old lavas towards the outer side of the arcs.

Thus, the rims of volcanic seas on the Earth and Moon are formed similarly by arcuate mountains with thrusting towards the outer side. The arcs bend differently and their geometrical regularities vary. The rises, whether on land or in seas, are always composed of older rocks, including old basaltic lavas.

On the Earth and Moon all differently arranged basaltic blankets of different ages form vast areas of the volcanic floor of seas and oceans. The oceans on the Earth and Moon can be of two types.

Pacific type. Old lava blankets are situated in the centre of the ocean and the young ones on its margins. This is how lunar Imbrium and Australe maria are formed. Each marginal basaltic basin is similar to a single volcanic mare of the Moon. It has a rim, i.e. a surrounding made up of the raised substrate. The zone of lava eruptions of each subsequent global impulse of volcanism becomes smaller.

Along the margin of shrinking lava basins the "mutually enclosed" arcs or rims with deformed old lavas appear. Ocean coasts are represented by mountain chains.

Atlantic type. Older lavas here are located along the ocean margins, and the younger ones, together with median ridges, in the centre. Such is the structure of the Oceanus Procellarum on the Moon. The mid-oceanic ridges are similar to converged and mutually straightened rims of adjacent gigantic concentric bands. Inside each of them the youngest basalts are located on either side of a common separating rim.

The formation of the Atlantic-type seas and oceans with their median ridges can be surmised as being a result of cycle-to-cycle increasing curvature radius of the rim bordering each consecutive lava basin occupying rear position. Finally, young basaltic blankets, gradually retreating from the middle of neighbouring global concentric bands, are moving towards each other. In such a manner appear "irregular" seas and oceans not bounded by mountain chains. Their inner areas belong to the margins of two or three adjacent concentric bands having converged rims.

The comparison of volcanic seas of the Earth and Moon has made it possible to catch a likeness in the formation of the basaltic floor of oceans on the two different planets. The origin of oceans is explained without using the assumptions of expansion of the planets and horizontal movement of their solid shell. Neither movement of "plates" nor spreading of the ocean floor are possible on the Moon. Old rims — fantoms flooded with ocean lavas retain their geometrically regular shape during submersion.

When the rims circling planetary basaltic basins are formed, the dynamics of the centrifugally propagating strain wave is the chief factor. This has made it possible to suggest a new hypothesis of "the centrifugal wave" in the development of the Earth geosyncline. The wave results from sub-surface shocks—explosions fed by internal energy of the Earth. The principle of the centrifugal wave can be applied for analysing ringed structures and circular volcanic seas of all terrestrial planets.

The appearance of each basaltic sea on the Earth and Moon is preceded by two acts of activation of the planetary interior.

(1) The appearing the concentric band of anorthosites that strengthens (cratonizes) the crustal substance is pushed out from the depths to the periphery.

(2) The mountain arc—rim is raised and granites or their homologues appear. It is only then that the third act is effected: basalts issue inside the formed arc. They overlie the behind-arc area that again acquires the property susceptible to deformation.

All three acts are interconnected and cause spatial differentiation of the primary substance of planetary covers. During initial stages of crustal development the earlier acts

are more effective when anorthosites form. The efficiency of intermediate acts of the endogenic triad, depending also on the planet's capability of retaining volatiles, increases with time. At least, the final acts of basaltic eruptions are most powerful.

The distribution of continents and lava-filled oceans on planetary bodies depends on sizes and arrangement of activated concentric bands of different ages.

A study of the Moon helps to answer the question of how the Earth's mountains and oceans appear. The Moon is a natural simplified model of our complicated and living planet.

TO THE READER

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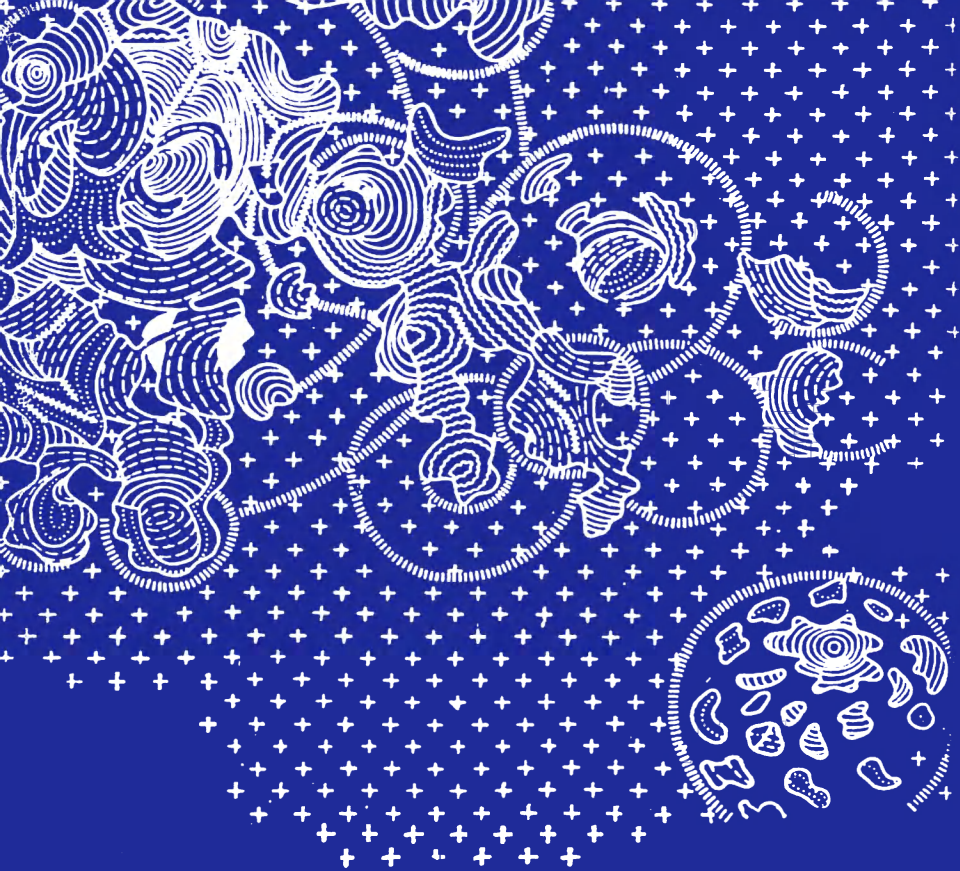
I.A. Rezanov. *Catastrophes in the Earth's History.* 167 pp. 1984.

This book is about the major natural catastrophes, both recorded and conjectural, that are known to modern science and which have led to changes in the outlines of seas and continents, and of the relief and climate of our planet. The book is intended for a wide readership. The present booklet has been published in Japanese, German, Bulgarian, and French.

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Today the author is vigorously engaged in collecting new facts in the field of comparative planology.



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